International Geology Review

Vol. 3, No. 7 July 1961

PARTIAL CONTENTS

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published by the
AMERICAN GEOLOGICAL INSTITUTE

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International Geology Review is published monthly by the American Geological Institute with the assistance of an initiating grant from the National Science Foundation. The journal will report, in English, significant contributions to pure and applied research in the earth sciences which appear in foreign-language journals, especially those published in the U.S.S.R.

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CONTENTS

IGR TRANSLITERATION OF RUSSIAN

The AGI Translation Office has adopted the Cyrillic transliteration recommended by the U. S. Department of the Interior, Board on Geographic Names, Washington, D.C.

Alphabet		transliteration
А	а	a
Б	б	b
В	в	v
Г	г	g
Д	д	d
Е	е	e, ye (1)
Ё	ё	ë, yë
Ж	ж	zh
З	з	z
И	и	i
Й	й	y
К	к	k
Л	л	l
М	м	m
Н	н	n
О	о	o
П	п	p
Р	р	r
С	с	s
Т	т	t
У	у	u
Ф	ф	f
Х	х	kh
Ц	ц	ts
Ч	ч	ch
Ш	ш	sh
Щ	щ	shch
Ъ	ъ	"
Ы	ы	y
Ь	ь	'
Э	э	e
Ю	ю	yu
Я	я	ya

NOTES:

(1) "ye" initially, after vowels, and after ъ, ь ; "e" elsewhere; when written as "ë" in Russian, transliterate as "yë" or "ë".

Well-known place and personal names that have wide acceptance will be used. Some translations may include elements of previous German transliteration from the Russian; this occurs in IGR most commonly in maps and lists of references. The reader's attention is called to the following variations between German and English systems which may cause confusion when trying to check back to original Russian sources.

German	English
w	v
s	z
ch	kh
tz	ts
tsch	ch
sch	sh
schtsch	shch
ja	ya
ju	yu

TENTATIVE CONTENTS FOR THE AUGUST ISSUE

ROLE OF ISLAND ARCS IN THE DEVELOPMENT OF THE EARTH'S STRUCTURE[1]

By

V. V. Beloussov and Ye. M. Rudich

• *translated by Research International Associates* •

ABSTRACT

Convincing geological data show that oceanic structure of the earth's crust is secondary and ormed as the result of destruction and basification of the continental crust. This process goes on nder conditions of tension, of deep fault formation, and of strong basaltic volcanism.

Analysis of the structure and history of development of island arcs gives evidence enough to istinguish two types. Island arcs of the first type represent arching folded ranges, similar to ontinental folded arcs. They were formed in geosynclines, but in the process of basification the upporting interior massifs subsides, while the arcs themselves are preserved in the form of urved bands of the continental crust within the oceanized areas (Japan, Indonesia, the Antilles). During a process involving tension of the earth's crust these weakened geosynclinal zones became reas of large fracture formation initiating intensive volcanism.

Arcs belonging to the second type are not related to the previous geosynclinal development. They were formed as a direct result of tension of the earth's crust, in the environment of ocean evelopment. The tension produced deep faults, and the curving of the trajectories of the tensional tresses in the process of fault growth gave rise to the arching of these faults. Being younger, arcs f the second type cross those of the first type.

The asymmetry of the Pacific Ocean is characterized by the fact that on the east the ocean is ordered by the Cordilleras and the Andes, forming a single weak zone, while on the western eriphery of the ocean the crust resembles a mosaic with very heterogeneous structure.

Basification of the earth's crust and formation of oceans is the last known stage in the development of the earth, caused by radioactive heating of the earth's interior and subsequent smelting o the surface of the deep material of the mantle. --author's English summary.

* * *

The problem of island arcs has been reviewed n the literature on more than one occasion. Two circumstances condition the author's new pproach to these questions. First, tectonic nd geophysical investigations were carried out n 1956 to 1959 in the Far East, in the transition rea between the Asian continent and the Pacific Ocean, by a group from the Academy of Sciences f the U.S.S.R., Institute of Physics. A member of the team was entrusted with the fulfillment of the IGY program. On that occasion new material was collected and previous data were ubjected to new analysis. Secondly, the authors attempt to consider the problem of island rcs against the background of general concepts f ocean rift formation and terrestrial development as a whole. They are certain that only such a eneral approach may lead toward its solution.

One of the authors has already pointed to the eologic evidence in regard to the youthful ppearance of oceans (Beloussov, 1951). Further analysis of these data has corroborated their absolute conclusiveness. It follows, at least, that the oceans extended their area at the continents' expense and became considerably deeper. There is no doubt, that mediterranean-type seas have formed recently, still further increasing the oceanic area. This viewpoint has been sustained by M. V. Muratov (1957), V. V. Tikhomirov (1958), and Yu. M. Sheynmann (1959).

Previously published works were concerned with: 1) a generally "superimposed" character of the Atlantic and Indian Oceans in relation to the structure of continents; 2) the existence of high, dry land in the lower Paleozoic to the northwest of the present Scandinavian peninsula, as follows from the direction of drift of Cambrian and Silurian sediments; 3) considerably better land connections between South America, Africa, India, Australia and Antarctica in the upper Paleozoic, as compared to subsequent times, this being proven by a specific Gondwanian flora distribution; 4) the obvious past distribution of the continental Karoo formations in South Africa, beyond the limits of contemporary boundaries of the continent; 5) the traces of upper Paleozoic glacial invasion, which originated from the direction of the contempo-

[1]Translated from O meste ostrovnykh dug v istorii razvitiya struktury zemli: Sovetskaya Geologiya, no. 10, p. 3-23, 1960.

rary Indian Ocean, yielding granite boulders of that source; 6) the paleogeographic evidence of high dry land east of the Appalachians, during the Paleozoic, apparently in place of the contemporary Atlantic Ocean; 7) the existence in the lower Mesozoic of dry land west of the contemporary African coast, as follows from the direction of the source of clastic formations in the Congo River basin; 8) the presence of indisputable geologic data corroborating the fact that the internal seas of the Indonesian archipelago, just as the South China, East China, Japan, Okhotsk and Bering seas, formed as a result of crustal subsidence, and only recently, no earlier than middle Tertiary, in place of then existing land units; 9) the presence of convincing geologic data pointing to the youth of the Carribean Sea, which subsided during the post-Cretaceous; 10) the formation, during the Tertiary and Quaternary, of the northern part of the Atlantic Ocean, as follows from reliable paleogeographic data; 11) the youth of the western Mediterranean Sea, where uplifted dry land still existed during the Paleogene; and 12) the youth of the Black Sea.

The following findings have corroborated the recent deepening of the oceanic depressions: 1) summits truncated by erosion are situated at various depths down to 2.5 km; 2) shallow-water sediments not older than Upper Cretaceous on summits of sea mounts; 3) subsidence by about 1,300 m of the bottom of reefs during the Tertiary, as shown by the results of drilling on coral reefs; and 4) littoral monoclinal flexures indicating recent tectonic deflection of the oceanic depressions.

All these data, combined with those concerning volcanism, its character and volume, and the distribution of volcanos in the oceans permits us to consider the oceans as zones of the strongest fissuring and "crumbling" of the earth's crust, and of enormous volumes of basalt effusions. The inescapable conclusion is that the oceanic structure of the earth's crust is secondary, and is the result of disintegration, reworking and replacement (basification) of the continental-type crust. This process of continental crust disintegration and "basification" takes place in the form of expansion and fracturing, accompanied by strong basaltic volcanism.

Objections have been raised more than once concerning these representations. They are principally based on the impossibility of the presumed process of continental crust destruction from the standpoint of energetics (Kropotkin et al, 1958; Lyustikh, 1959). However, in view of our nearly total ignorance of conditions existing at depths of several hundred kilometers, it is extremely dangerous to assume what processes are possible or impossible within the bowels of the earth. More and more of the existing geologic facts must be analyzed, and if they indisputably corroborate the hypothesis of oceanic crust formation in place of the continental, our obvious concern must be in seeking the explanation of such phenomenon no matter how difficult, and not in trying to avoid the facts.

If it is true that all the above-cited cases of development of oceans and formation of new seas occurred; then this transformation of continental crust into maritime must have taken place, as this crust is known to be oceanic in all subsided regions, and it would be quite unnatural to assume that it has formerly been such, when all these regions were uplifted dry land units. In the latter assumption all this would seem incredible -- the manner by which these abnormal units could have maintained themselves in an uplifted state, contrary to conditions of isostasy, and why these same units subsided at nearly the same time, while in our era, not a single such uplifted unit remained on the surface of the earth, and we observe a precise correspondence between two types of crust of the earth on one hand, and of continent and ocean boundaries on the other.

As a complement to the above considerations, we should like to introduce certain new data.

The oceanic structure of the crust has been disclosed by deep seismic soundings in the North Atlantic (Ewing and Ewing, 1959; Press, 1958). At the same time no one doubts that this region was flooded not earlier than the Tertiary. Similar investigations also disclosed an oceanic structure of the crust in the Black Sea (Neprochnov, 1958, 1959a, 1959b). The paleogeography of surrounding regions shows that in the course of all geologic history, and up to its very latest stages, only shallow-water basins existed in place of the Black Sea. This conclusion is also indicated for the southern part of the Caspian Sea, where seismic soundings have established the absence of the granitic layer (Gagelyants et al, 1958).

Extremely interesting data published by Behrmann (1958), shows that at the beginning of the Miocene, high dry land existed in place of the Tyrrhenian Sea, from which granite boulders were eroded. Meanwhile, gravimetric data point to an oceanic structure of the crust under that sea (Kropotkin et al, 1958).

Somewhat more detailed data will be presented for the Seas of Japan and Okhotsk, inasmuch as they are related to the territory where the island arcs of interest to us are mainly distributed (fig. 1).

By examining the distribution of rock facies and thicknesses of Paleozoic, Mesozoic and Cenozoic formations of the coastal region, of Sakhalin and Japan, we reach the following conclusions:

During the middle and upper Paleozoic a

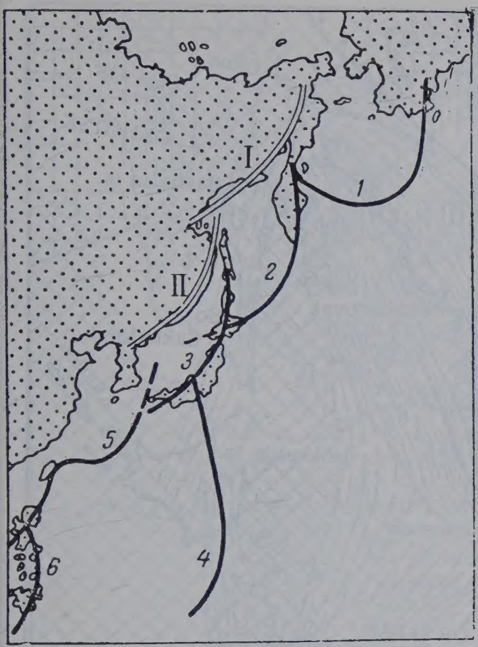

FIGURE 1. Island arcs of the western and northwestern parts of the Pacific Ocean.

Island arcs:
1 - Aleutian
2 - Kamchatka-Kuriles
3 - Japanese
4 - Bonin-Marianas
5 - Ryukyu
6 - Philippine

Mesozoic-Cenozoic volcanic zone:
I - Priokhotsk
II - Sikhote Alin

broad geosyncline existed in the place of islands of Sakhalin and Japan. Taking account of the great similarity of the Paleozoic developed in Japan and in the coastal region, it may be assumed that the Paleozoic geosyncline included not only Japan, but also the coastal region, and possibly the northern and central part of the contemporary Sea of Japan. It is probable that in the southern part of the sea a platform region existed (Murokoshi and Hashimoto, 1956; Kobayashi, 1949) (fig. 2).

The Hercynian stage of development of that geosyncline was culminated by the formation, in place of the contemporary Sea of Japan, of a central uplift, bounded on the east by a marginal depression situated in the outer zone of southwest Japan, the Abukuma and Kitakami mountains.

At the beginning of the Alpine cycle, this marginal depression was transformed into the Mesozoic intrageosyncline. These intrageosynclinal conditions existed simultaneously in the coastal region. The Upper Triassic sea transgressed not only intrageosynclinal depressions, but partly also the limits of the median massifs, having formed in place of the central Hercynian uplift.

The median massif of the Sea of Japan region was subsequently subjected, at different epochs, to intense uplift and erosion. Judging from data by Khudoley, this region was on more than one occasion during the Jurassic a source of sediments accumulating in the Sikhote Alin geosyncline. The same investigator has shown that the volume of sediments which accumulated during the Jurassic in the intrageosyncline extending along the eastern slope of the contemporary Sikhote Alin considerably exceeds the volume of the eroded Permian sequence which composed the central uplift in the Jurassic. The existence at that time of dry land in place of the contemporary Sea of Japan is corroborated not only by the direction of the drift of material, and the repetition of the facies of Jurassic formations within the limits of the Sikhote Alin geosyncline (fig. 3), but also by a varied composition of the coastal region and Jurassic fauna of Japan.

Development of the South Honshu intrageosyncline continued in Japan during the Jurassic. The regular accumulation of marine deposits widely distributed in the outer zone of southwestern Japan replaced by shallow-water and continental sediments, also points to the existence of dry land within the limits of the Sea of Japan.

The relatively quiet development of the Japan and coastal intrageosynclines continued to the end of the Lower Cretaceous.

An inversion with formation of a central uplift occurred in south Honshu intrageosyncline during the Cenomanian-Turonian. At the same time a strong phase of folding took place in Japan.

In the coastal region, the Upper Cretaceous was marked by a broadening of the central upheaval, gradually moving to the marginal depression of Sikhote Alin, and by intense folding. Evidence for these movements are represented in the Upper Cretaceous sequence, by alternating marine and coarse, clastic, continental sediments.

The Hokkaido-Sakhalin region developed in a quite different way during the Mesozoic. At the end of the Hercynian cycle a major uplift occurred here, related to the epi-Caledonian platform of Okhotsk. The continental regime was preserved here during the Triassic, Jurassic, and the first part of the Cretaceous in a great part of the territory. During the Middle Jurassic, the subsidence obviously spreading from the Kitakami zone, overtook the southern part of central Hikkaido. During the Cretaceous

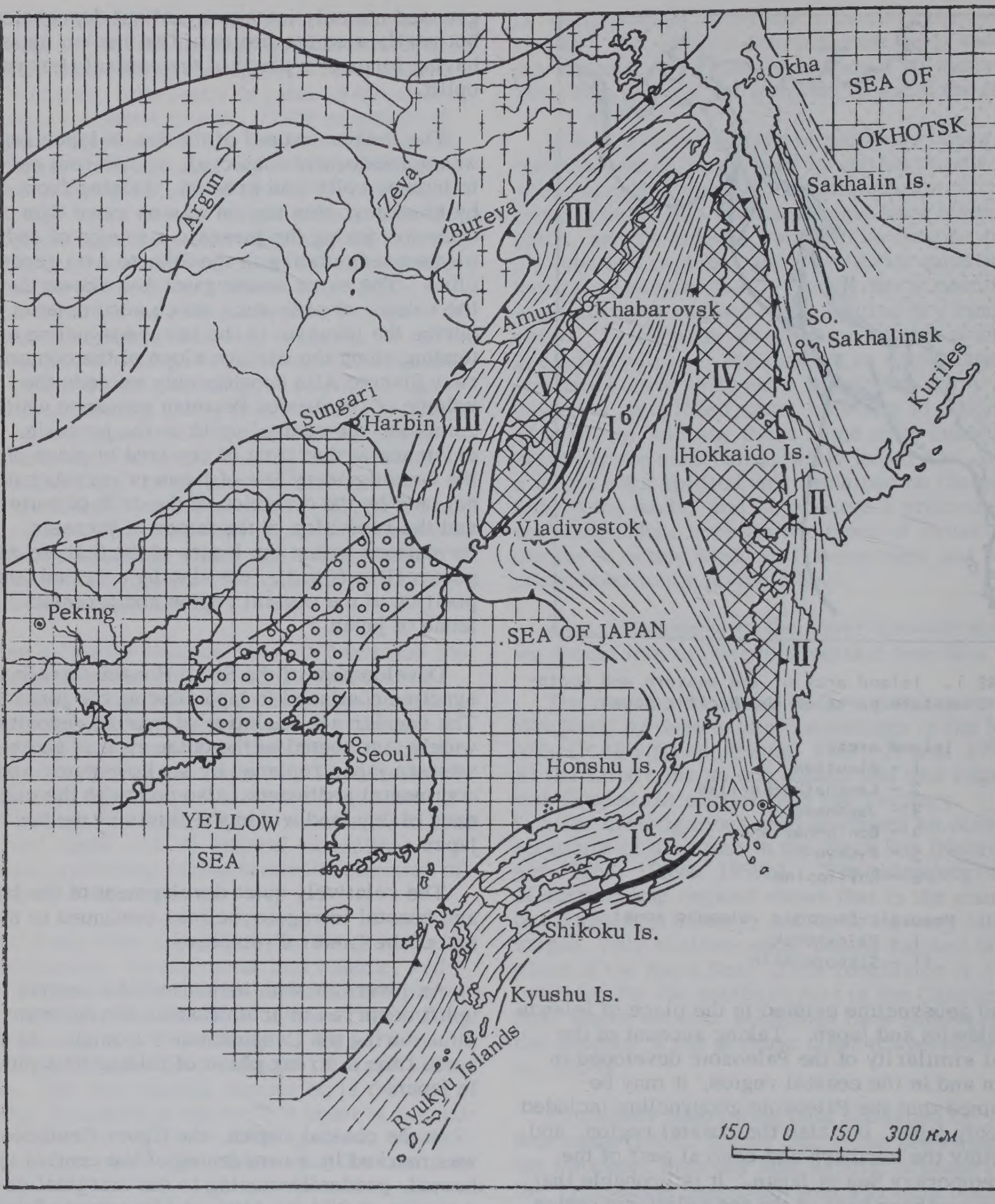

FIGURE 2. Paleotectonic map, end of Hercynian

1-- subgeanticlines;

2 - subgeosynclines;

3 - region of Caledonian folding

4 - Mongol-Okhotsk parageosyncline

5 - Hercynian intrageosynclines:
Ia - South Honshu
Ib - Sikhote Alin
II - Hokkaido-Sakhalin
III - East Manchurian

6 - Hercynian intrageanticlines:
IV - Hokkaido-Sakhalin
V - Khankay

7 - zone of maximum bending in limits of intrageosynclines;

8 - borders of intergeosynclines;

9 - borders of strong tectonic zones

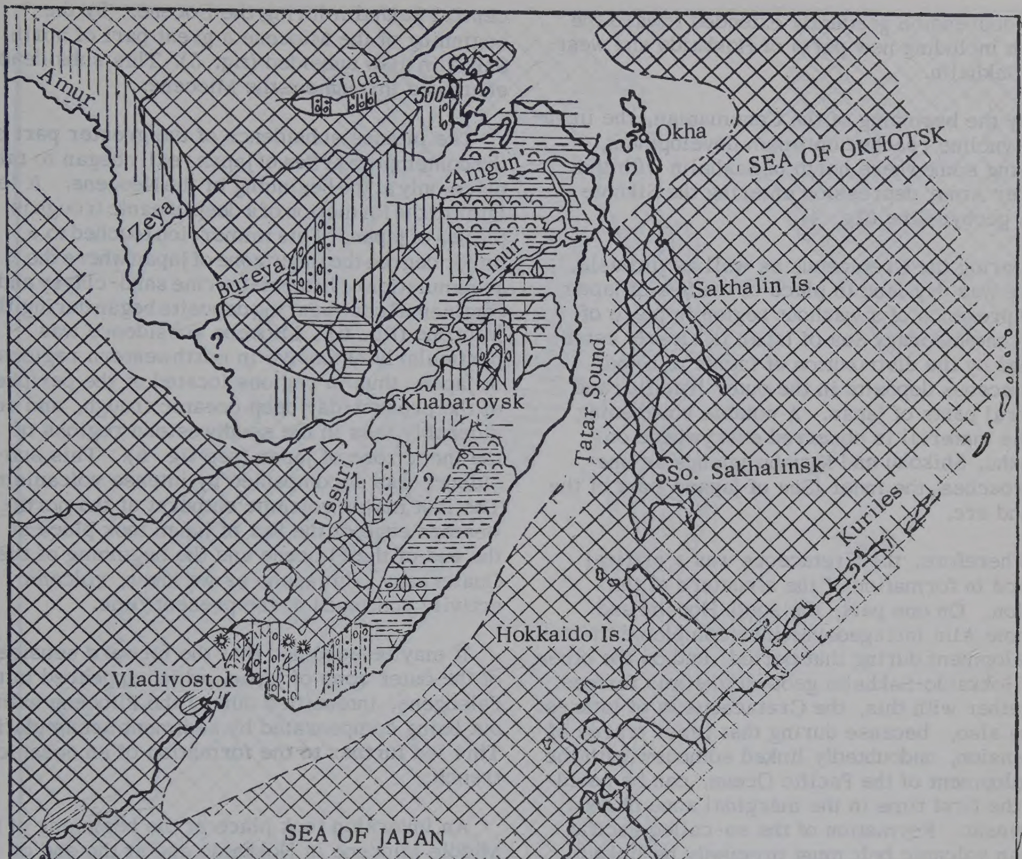

FIGURE 3. Paleogeographic map, Lower Jurassic

Character of deposits: 1 - open sea 2 - circumlittoral-oceanic 3 - alternating circumlittoral-oceanic and continental 4 - continental 5 - erosion region

Composition of deposits: 6 - carbonates 7 - clayey 8 - sand conglomerates 9 - effusives 10 - tuffogenic 11 - siliceous and silico-argillaceous

12 - thickness of Lower Cretaceous deposits 13 - boreal fauna 14 - warm-water fauna 15 - volcanoes 16 - borders of paleogeographic zones; established 17 - the same; assumed

this depression gradually extended toward the north including new parts of Hokkaido and western Sakhalin.

By the beginning of the Cenomanian, the intrageosyncline reached optimum development, closing somewhere north of Sakhalin with the Lower Amur depression entering the Sikhote Alin geosyncline (fig. 4).

During the Cretaceous as well as Jurassic, there was dry land in place of the Sea of Japan. The presence of a washout region in place of the contemporary Sea of Japan is clearly established by the distribution of facies of Upper Cretaceous deposits in the outer [Pacific] and central parts of Japan. A notable roughening of the material is observed everywhere on Honshu, Shikoku and Kyushu islands as one approaches the inner [Sea of Japan] part of the island arc.

Therefore, the Cretaceous was a critical period in formation of the structure of the region. On one part, the south Honshu and Sikhote Alin intrageosynclines completed their development during that period, and on the other, the Hokkaido-Sakhalin geosyncline was formed. Together with this, the Cretaceous is of interest to us also, because during that time, traces of expansion, undoubtedly linked somehow with the development of the Pacific Ocean, can be noted for the first time in the marginal zone of Asia continent. Formation of the so-called Pacific Ocean volcanic belt must precisely be linked with formation of these fractures, the former extending in an uninterrupted band from China to Anadyr, and marked by a band of powerful effusions of mostly andesitic or andesite-basaltic lavas. An opinion has been expressed that this belt represents the trace of older, destroyed Mesozoic-Cenozoic island arcs (Ustiyev, 1959). We shall refer to this question later.

The inner massif of the Sea of Japan maintained a steady trend of uplift during the Paleogene. It is possible, that at the time there was a certain reinforcement of ascending tectonic movements in that region. Judging from data by N. A. Belyayevskiy, there existed during the Paleogene in place of the Sea of Japan some source of products of granite disintegration. Along the northwestern edge of the future Sea of Japan a zone of active volcanism continued to exist (fig. 5).

In the outer zone of southwestern Japan, there appeared during the Paleogene a depression at the foot of the central uplift to the south. Coarsely fragmental littoral-marine sediments accumulated in that depression, extending from the southeastern end of Kyushu to the center of Honshu.

Subsidence resumed in the Hokkaido-Sakhalin intrageosyncline during the Paleocene. Gradually widening northward, the geosyncline reached central Sakhalin during the Eocene. By the beginning of the Miocene a great part of north Sakhalin also subsided (fig. 5). This subsidence continued throughout the Miocene.

The intense subsidence of the greater part of the contemporary Sea of Japan really began to take place only at the beginning of the Neogene. It led later to the formation of a deep oceanic trough in the Sea of Japan. This immersion touched to a minor degree the inner zone of Japan where the accumulation of littoral-marine sand-clayey and continental coal-bearing deposits began during the Miocene (fig. 6). Miocene subsidence was particularly extensive in northwestern regions of Japan, thus in regions located at the periphery of the present-day deep oceanic trough, and considerably less in the southwestern regions of the inner zone of Japan (see fig. 6). This subsidence was accompanied by intense volcanism. The last major volcanic outburst at the northwestern edge of the Sea of Japan took place at the end of the Pliocene and the beginning of the Quaternary. In Japan, as we know, volcanic activity continues at the present time.

It may be assumed that the forward subsidence of the outer zone of Japan, which appeared in the Paleogene, intensified during the Pliocene without being compensated by sediment accumulation. This led further to the formation of an oceanic trench.

An inversion took place at the beginning of the Middle Miocene in Hokkaido and at the end of the Miocene in southern and central Sakhalin, and the geosynclinal depression was divided into a pair of marginal depressions by a central uplift. At the north of Sakhalin, where Tertiary sediment accumulation began with great delay, the inversion revealed itself to a lesser degree than in more southerly regions, with uplifting and folding during latest Pliocene. In contrast to the southern region of the island northern Sakhalin was characterized during the Tertiary period by parageosynclinal conditions (Rudich, 1958)

The whole course of the geologic history of the region, as well as the paleogeographic data, corroborating the presence within the limits of the Sea of Japan of areas of erosion at the end of the Paleozoic, during the Mesozoic and Paleogene, lead to the conclusion that in the course of all that time, a continental-type crust existed in the Sea of Japan. The oceanic trench of the Sea of Japan was not formed until the beginning of the Paleogene (in the northwest), and the Neogene (in the east). Appearance of the trench was preceded by an intense uplift and the denudation of the granite layer of the crust, and its development was accompanied by a basic and neutral volcanism (Kuno, 1959). Inasmuch as at the present time the crust under the Sea of Japan is oceanic (Andreyeva and Udintsev, 1958; Sysoyev et al, 1958), it may be inferred that the

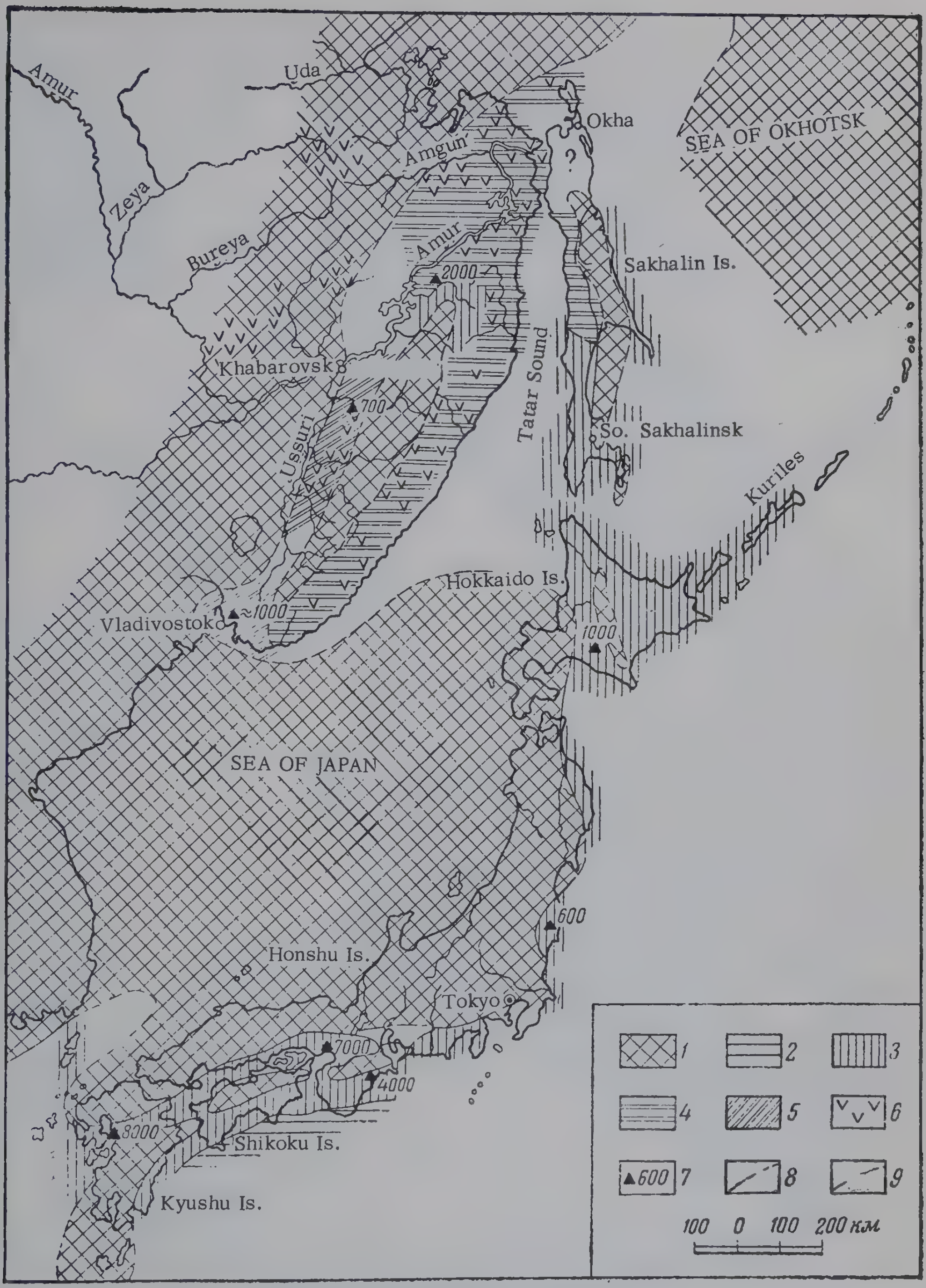

FIGURE 4. Paleogeographic map, Upper Cretaceous

1 - erosion region

Character of deposits: 2 - open sea 3 - circumlittoral-oceanic 4 - alternating circumlittoral-oceanic and continental 5 - continental 6 - subaerial volcanism

7 - thickness of Upper Cretaceous sedimentation 8 - borders of paleogeographic zones; established 9 - the same, assumed.

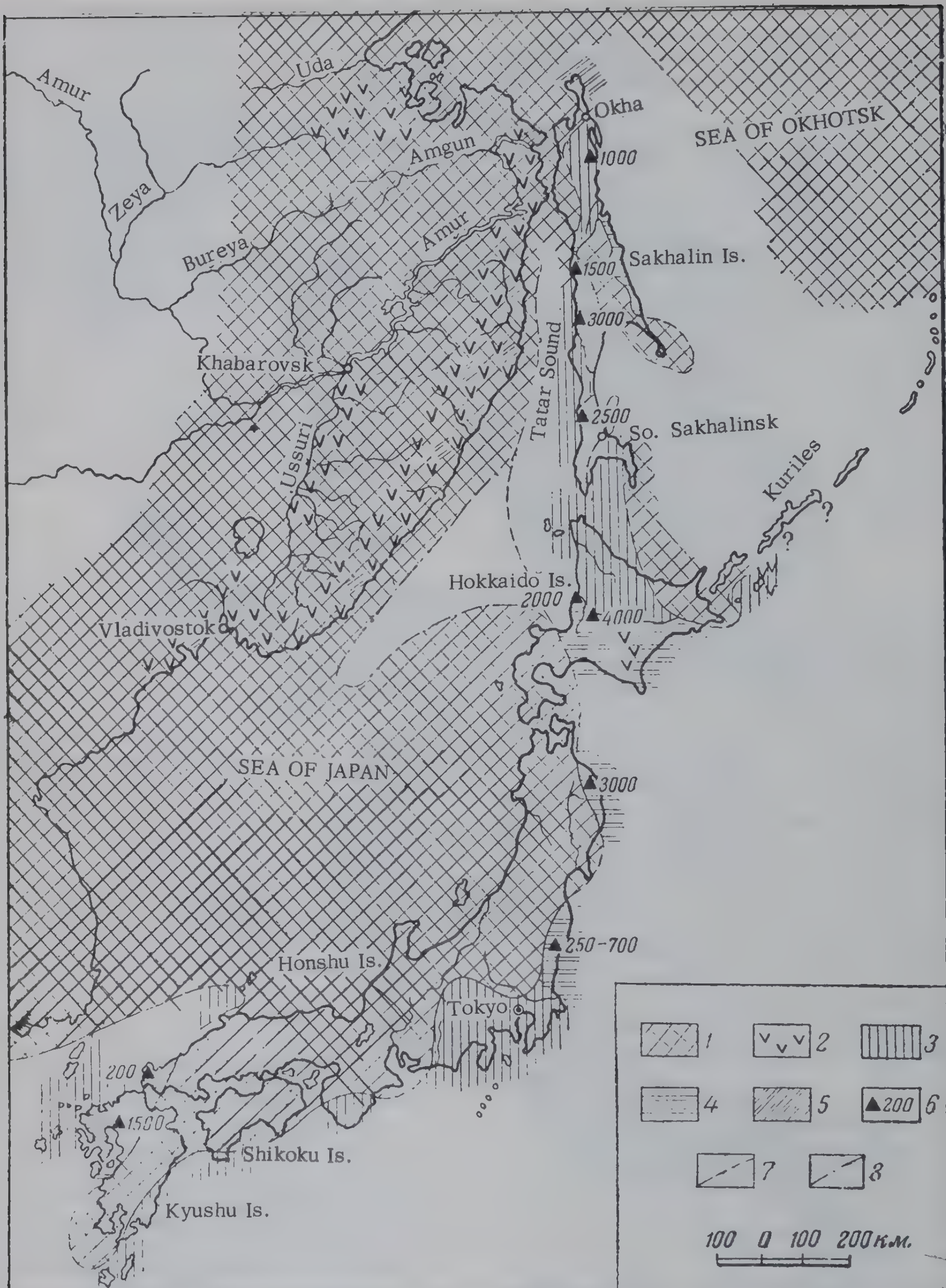

FIGURE 5. Paleogeographic map, Paleogene

1 - erosion region 2 - subaerial volcanism

Character of deposits: 3 - circumlittoral-oceanic 4 - alternating circumlittoral-oceanic and continental 5 - continental

6 - thickness of Paleogene deposits 7 - borders of paleogeographic zones, established 8 - the same, assumed

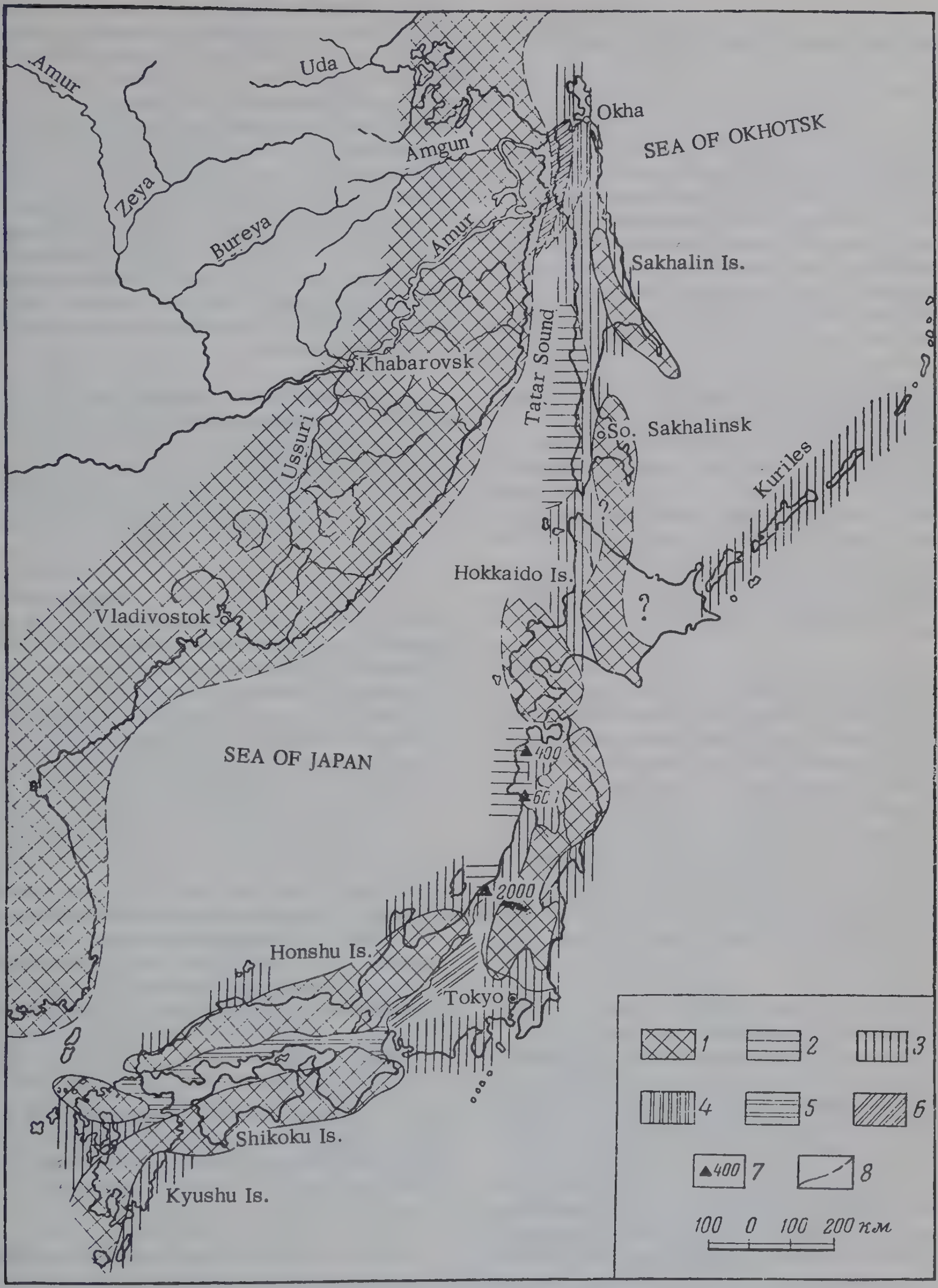

FIGURE 6. Paleogeographic map, Miocene

1 - erosion region

Character of deposits: 2 - open sea 3 - circumlittoral-oceanic 4 - alternating circumtoral and lagoonal 5 - alternating circumlittoral and continental 6 - continental

7 - thickness of Miocene deposits 8 - borders of paleogeographic zones, established and assumed.

terrestrial crust of the central part of the Sea of Japan underwent a radical transformation.

Reconstitution of the history of the Sea of Okhotsk presents a more complex problem. There probably was a platform in place of the Sea of Okhotsk , representing, during the Paleozoic and the Mesozoic either dry land, or a shallow sea. During the Upper Cretaceous the outskirts of this platform were covered by an epicontinental sea. Here, the accumulation of volcanic rocks took place alongside the sedimentary deposits. The presence of an erosion territory in place of the Sea of Okhotsk is noted during the Paleogene (B. F. Dyakov). The beginning of formation of the deep-water sea of Okhotsk trench, and the formation of the Kurile island arc is related to the end of the Tertiary and the beginning of Quaternary according to A. B. Goryachev. G. B. Udintsev (1957) dates the appearance of the contemporary Sea of Okhotsk water area as Quaternary. P. V. Ushakov (1950) has found convincing signs of extreme youth of the deep trough of the Sea of Okhotsk. Thus, the history of geologic development of Japan, the coastal region, Sakhalin and the Kurile islands shows that the deepwater troughs of the Sea of Japan and of Okhotsk are very young.

In this connection it is interesting to note that in the shallow-water littoral sectors of the oceans have been preserved more archaic forms of life than in the abyssal regions. Only a single Paleozoic relic has been known from great depths (Neopilina). Among deep water Foraminifera 86 percent are of Tertiary age, 14 percent are Mesozoic, and none are Paleozoic. Therefore, there is all the more reason to consider that the abyssal fauna is very young, and that it is mostly of Tertiary age, a fact which supports the idea that troughs of the oceans are generally young (Menzies and Imbric, 1958).

In the light of all data brought forth, the assertion that a continental crust may transform into oceanic and result in the "oceanization" of the given terrestrial unit appears to us as being well founded. If this process of oceanization develops in marginal and inland seas, why could not it manifest itself over broader ocean surfaces? Especially because oceans, as we had the opportunity to see, are beset with a process of intense deepening, which, under conditions of isostasy, must unavoidably be accompanied by transformation of the crust, and of the substratum underlying it.

It is unfortunate that we cannot contribute anything substantial to the general consideration as regards the mechanism of crust basification expressed earlier (Tikhomirov, 1958). It is probable that the question must evolve around the basic metasomatism and also the fusion and the dissolution of the granitic layer. The cause of these processes must lie in the ascent of superheated basalt from the bowels of the earth. If we assume the composition of the upper part of the mantle to be eclogitic (an assumption which now seems the most probable (Lovering, 1958)) there is no longer any obstacle for a possible participation of enormous masses of superheated basalts in the basification process by interaction with the thin granite layer. From this point of view, those basic anatexis phenomena to which Michot (1956) refers, have great interest. At the end of this paper, the authors will briefly state certain considerations on the possible direction of the general evolution of the terrestrial globe from that point of view, but these questions will be more particularly dealt with in another work.

Island arcs are, as is known, a characteristic of the northern and western parts of the Pacific Ocean, Indonesia, Antilles, and South Sandwich archipelagos. All are formed by folded or volcanic structures of the young Alpine cycle. Study of structure and history of island arc development allows their subdivision into two types.

Island arcs of the first type represent curved, arcuate folded zones, similar to folded arcs on continents, such as, for example, the Himalayas, Carpathians, Verkhoyansk Range and others. The arcuate form of these folded zones is linked with their history. The simplest sequence of events may be stated in the following manner: During the preceding tectonic cycle (the Hercynian for Alpine folded arcs), the geosyncline disintegrated into a series of ovals, connected by narrow bridges, which, generally speaking is quite proper to geosynclines. At the end of the cycle, during the inversion process, a central uplift appears inside the oval; it is bounded on both sides by arc-shaped forward depressions, which transform during the next cycle into intrageosynclines, and from which folded ranges rise as a result of a new inversion. These ranges have quite naturally an arc-shaped form. At the same time, the central uplift of the preceding cycle subsides somewhat, and forms in the young geosyncline what is usually designated as the median massif. Such, for example, is the mutual relationship of the Carpathians with the subsided Hungarian median massif, of the Himalayas and the Tibet median massif, of the Verkhoyansk folded zone and the Kolymsk median massif.

There is no doubt that the nature of the folded arc bordering the western part of the Mediterranean Sea is similar, and that it is now to a considerable extent situated in a subsided median massif of the Alpine geosyncline. Paleogeographic data allow us to consider that the same type of median massif existed in place of the Carribean Sea, inside the Antilles island arc (Butterlin, 1956). Investigations by van Bemmelen and other geologists in Indonesia left no doubt that Indonesian arcs are of the same nature,

and represent young, folded uplifts framing the presently immersed median massif (van Bemmelen, 1955).

A review of geologic history leads to the conclusion that Japan may also be referred to the same category of island arcs. In fact, it may be seen from the preceding review, that the northwestern part of the southern half of Honshu island was involved in the uplift and underwent granitization and metamorphism at the end of the Paleozoic, while the outer side of the same southern half of Honshu Island was a marginal depression. We have seen that the upper Paleozoic upheaval was not limited to the narrow band of the inner side of the island, but encompassed the greater part, if not all of the Sea of Japan, as may be seen from the paleogeographic data. The upper Paleozoic marginal depression developed within the Alpine cycle as an intrageosyncline, and the uplift in place of the Sea of Japan has played in that cycle the part of the median massif. During the Tertiary, this massif was raised above the sea level through the end of the Paleogene, and its subsidence began only during the Miocene, as was previously shown.

The most distinctive characteristics of this type of arc is that they were formed in geosynclinal zones of the crust, weakened by numerous deep-seated fractures during their deposition. They represented folded ranges formed in Alpine intrageosynclines, and having acquired the shape of island arcs precisely because the medium massif located within them, had deeply subsided in the course of the basification of the crust, and the process of oceanization.

The subsidence boundaries may not exactly correspond to the outline of the median massif, part of which may remain uplifted. This is observed in Japan, for example, where a considerable part of the main island consists of an uplifted edge of the median massif whose fundamental part is at the bottom of the Sea of Japan. The same phenomena are observed in Indonesia (van Bemmelen, 1957).

A deep ocean trench, always accompanying such a type of island arc, begins to develop initially in place of a forward geosynclinal depression, but later, and as it finds itself within the sphere of oceanization processes, the subsidence takes place so fast, that it is not compensated by sediment accumulation.

Island arcs of the second type differ substantially. Islands within this category, either are Tertiary or Quaternary, or blocks of weakly dislocated Cretaceous or Tertiary deposits. The Aleutian, Kurile, Ryukyu, and Bonin-Mariana arcs are related to this type. They had no geosynclinal pre-history, and are most probably linked in formation with the appearance of new deep-seated fractures in the crust of the earth, whose geosynclinal development was completed long before the appearance of island arcs. Some of these arcs are bounded by regions which were dry lands in fairly late geologic time (for example, Sea of Okhotsk, Bering Sea).

Arcs of the second type are as a rule younger than arcs of the first type. This may be seen in the example of the intersection of the Japanese arc by those of Kurile and Bonin-Mariana. It is known that Honshu island is cut in two by a major tectonic break (Fossa Magna) exactly in the extension of the Bonin-Mariana arc, and that the two halves of the island have different structures since vertical displacement took place between them.

Besides, in the prolongation of the Bonin-Mariana arc a zone of negative gravity anomalies is noted, which attests to the thickening of the crust (Tsuboi, 1956). Finally, a change in the trend of gravity isoanomalies from northeastern to northwestern, according to the Bonin-Mariana arc strike, is also observed here (Tsuboi, 1954).

A band of Tertiary and Quaternary volcanoes on Hokkaido is aligned in extension of the Kurile arc, completely independent of Paleozoic and Mesozoic structures.

Tectonically the Bonin, Mariana and Kurile arcs do not terminate on Honshu and Hokkaido but, crossing them, extend toward the Sea of Japan. The reviewed arcs are accompanied by epicenters of deep-focus earthquakes. The latter form bands extending parallel to the inner side of the arcs, and this is linked with the sloping of focal surfaces toward it. These bands of deep earthquake epicenters meet the Japanese arc, extend through Sakhalin and Honshu into the Sea of Japan, and meet one another near the coast, in spite of the fact that no morphological evidence of young island arc extension in this direction is noted (fig. 7). We may assume the following sequence of events: formation of the Japanese folded arc, then formation of the Kurile and Bonin-Mariana arcs which intersected the first arc, and next after that subsidence of the Sea of Japan, obliterating the outer evidence of the extension of these young arcs to the center of the Sea of Japan.

Within the limits of at least some of the arcs of the second type a certain sagging of the crust of the earth took place, and, beginning in the Upper Cretaceous, sediments of moderate thickness were accumulated, later to be raised in the form of blocks, while the land units behind them subsided.

However, the rate of sagging and the character of subsequent dislocations in these arcs precludes any comparison with typical geosynclines. At the same time, arcs of the second type are clearly connected with the deep-seated fractures of the crust of the earth, having

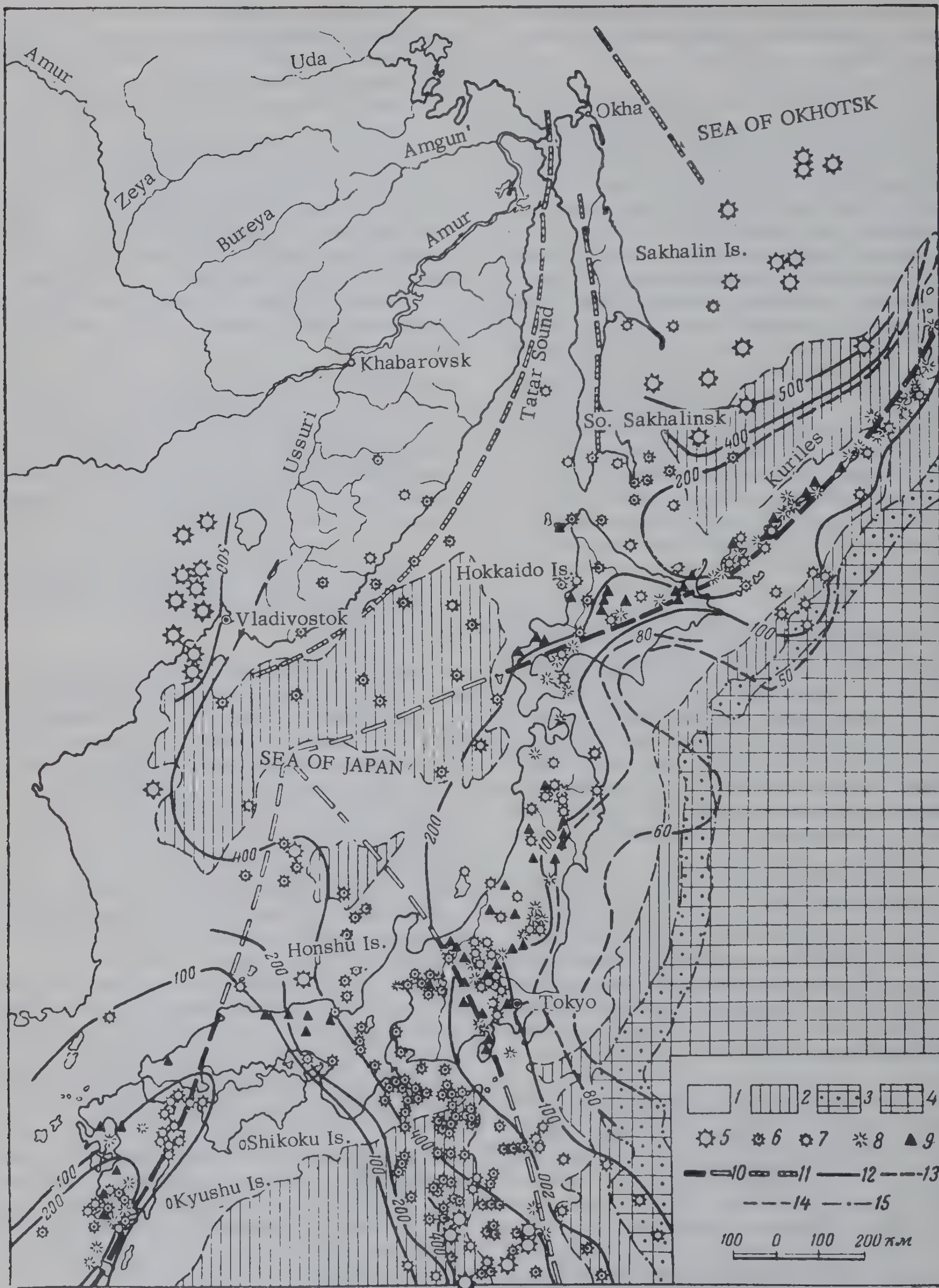

FIGURE 7. Structure of crust, deep-focus earthquakes and volcanism in the Sakhalin-Japanese arc

1 - regions with a continental type crust 2 - oceanic depths with crust of oceanic or intermediate type 3 - oceanic trenches (zones of greatest elongation and thinning of crust) 4 - shelf of Pacific Ocean with oceanic type crust 5-7 - epicenters of deep-focus earthquakes with depths of more than 400 (5), from 400 to 200 (6), and less than 200 km (7) 8 - active volcanoes 9 - extinct volcanoes 10 - recent deep ruptures, along which type-2 arcs have appeared 11 - other deep ruptures 12,13 - seismic isobaths in km (for deep-focus earthquakes) 14 - borders of oceanic depths (3,000 m isobath) 15 - borders of oceanic trenches.

created favorable conditions for the development of intense volcanism.

It is pertinent here to reconsider arcs of the first type, so as to note in the newest development certain elements in common with arcs of the second type. This resemblance consists in an intense Tertiary and Quaternary andesitic and basaltic volcanism, whose activity considerably exceeds that of usual continental geosynclinal zones. We can assume that the formation of deep-seated fractures has also contributed to the increase of volcanism, but if at the time of formation of arcs of the second type, these fractures reappeared, then in the case of arcs of the first type during the formation of fractures, the process may possibly have been reduced to a supplementary reopening of pre-existing fractures, just as the young geosynclines may have used the weak spots during fracture formation.

From this viewpoint it is interesting that the northern part of the Japanese arc includes the islands of Hokkaido and Sakhalin, where, in studying the history of sediment accumulation, it is possible to note the gradual spreading of the Alpine depression toward the north: on Hokkaido the sedimentation begins during the Middle Jurassic, on Southern Sakhalin this happens only toward the end of the Lower Cretaceous.

It may be assumed that at time of formation of new fractures, or of widening of the old ones, which coincided with the Japanese alpine geosyncline, a gradual "rip opening" of the unit located to the north took place, and at the same time a gradual spreading to the north of the zone of active crustal movement, albeit with diminished intensity. In that direction it changed from a geosynclinal stage of Hokkaido, to a parageosynclinal on north Sakhalin. Thus, this northern part of the Japanese arc is likely to be closer in origin to arcs of the second type, but forming as a result of the spread to the north of those fractures which appeared in connection with the strictly Japanese arc of the first type. This example shows that in separate cases the development of major elongated fractures in the crust of the earth was not accompanied by the formation of the island arcs proper, but of geosynclines or parageosynclines.

It must be borne in mind that island arcs of the first and second type are the extreme members of a continuous series, mutually connected by gradual transitions. That is why, in relation to island arcs, fully characterized as arcs of the first or of the second type, one may observe in nature arcs or parts of arcs, which in structure and development patterns combine the characteristics of both types.

The process of fracture rejuvenation and volcanism intensification is also observed in the Antilles arc. It is interesting to note that it manifests itself here last in that part closer to the Atlantic Ocean, and it is expressed in the form of volcanism in the Lesser Antilles (Butterlin, 1956). One may assume that the formation of most volcanic complementary arcs, on the side of arcs of first type, which is especially typical of Indonesia, is one of the consequences of "rejuvenation" of earlier geosynclinal deep-seated features, and the rising of magma along them.

Other peculiarities of the structure and the development of island arcs are better examined with the discussion of the general causes of their formation.

The aggregate of all geological phenomena accompanying the formation of oceanic troughs indicates that their development takes place within the framework of crustal expansion. Confirmation is to be found everywhere. Principal confirmation lies in the strong development of basalt volcanism at the bottom of the oceans, obviously linked with the deep-seated expansion fractures. These expansion fractures may also be seen along the Atlantic coasts of Scotland, Iceland, and Greenland, where manifestations of intense Tertiary and Quaternary volcanism are ascribed to them(van Bemmelen, 1955). The expansion grabens of east Africa, including the Red Sea graben may also be related to the same order of phenomena. These grabens may be considered as forerunners of a further widening of the Indian Ocean. The enormous volcanic belt surrounding the Pacific Ocean is sufficient sign of crustal expansion along its periphery.

It is on such expansion conditions that are formed those deep-seated fractures, which are either formed anew, as observed in connection with arcs of second type, or are the results of a rejuvenation of already marked geosynclinal fractures, as for example, in the case of arcs of the first type. From this standpoint, the results of geophysical investigations of the structure of deep trenches surrounding the island arcs are of utmost interest, and particularly the Puerto Rican trench. These investigations reveal in the trench structure obvious signs of expansion accompanied by sinking of the crust (Ewing and Heezen, 1957).

Curvature of the arcs of the second type apparently stems from the phenomenon reviewed by M. V. Gzovskiy (and Chertkova, 1953) in connection with study of tectonic crack undulation. He has shown that after the inception of a small expansion fracture, it does not progress rectilinearly, but by bending in an arch. This results from the fact that appearance of a fracture, while changing the state of tension in its vicinity, leads to a curving of maximum elastic trajectories.

The resulting deep-seated fractures constitute

outlets for volcanic material. Aside from that, they constitute zones in which differentiation within the mantle of the earth is facilitated. Such differentiation is translated at its inception into a form of undulating oscillatory movements at the surface, i. e., development of depressions and uplifts. It was already indicated earlier, that such undulating oscillatory movements may be viewed as the most probable surface reflection of deep-seated processes of substance differentiation, when in certain areas light materials flow up, inducing the uplift of the crust of the earth, while nearby, this flow is being compensated by a descent of heavier material with the formation of a sag at the surface (Beloussov, 1951). Such a differentiation inducing wave-like oscillatory movement is developed to a still greater degree in places where the fracture is a combination of a series of partial fractures occupying a certain zone, as is apparently, the usual case.

The result of the deep-seated differentiation process is a subdivision of the geosyncline into central uplifts, in forward and intermountain depressions. The opposition of deep troughs, bounding the island arcs of the first type, to uplift of the arc is linked to the same cause. The alternating of deep troughs and raised ridges within the structure of the arcs of the second type should naturally be related to the same category of phenomena connected with the differentiation of the subcrustal material, but on a lower scale than in typical geosynclines.

Therefore, the development of wave-like oscillating movements in the deep fracture zone, as a function of their intensity, influences the tectonic regime of such a zone by giving it the appearance of geosynclinal or parageosynclinal regimes.

This consideration leads to an understanding of the development of parageosynclinal conditions of North Sakhalin in the zone of fractures as having been the result of the developing trend of fractures of the Japanese geosynclinal arc. The mutual relationship of the Kurile arc and Kamchatka may apparently be interpreted in the same light, but, in view of the great volume of regional tectonic material to be referred to, it would be better to examine this question separately.

A certain asymmetry of the Pacific Ocean arouses attention, namely, the presence of island arcs along its western periphery, and their absence in the east. This asymmetry may be explained by the fact that, at a certain stage of its expansion, the oceanic trough reached in the east the single geosynclinal zone of the Cordillera and the Andes, considerably weakened by numerous fractures. As the crust of the earth "calved" during its basification and oceanization, and most likely sank in separate large blocks, it is quite natural, that the "calving" process ceased at a determined stage over such a line, as in a long-existing geosyncline.

Other conditions existed at the western end of the Pacific Ocean. There was no single structural zone, similar to the Cordilleras and Andes, and the crust of the earth had a mosaic structure, and consisted of alternating flat and folded units of different age and orientation. That is why the process of the crust expansion of the earth had adapted itself to geosynclines, which existed earlier, and were weakened by fractures, as for example, within the limits of the Japanese arc. In other cases, this process led to the formation of new fractures, thus inducing arcs of the second type.

During the initial stage of crustal fracturing and sagging of Pacific Ocean along its western edge, a powerful zone of fractures was formed, extending from China to Anadyr. This zone is known in contemporary geology as the Pacific Ocean Volcanic Belt.

It was initially formed during the Cretaceous, but did not, however, undergo a full subsequent development, and it did not transform into a typical island arc. It may be assumed that the unfinished character of the development of this zone is related to the fact that it was superposed to crustal units of various ages, having different structure and thickness, and being at a different stage of initial material differentiation, which obviously had not been completed anywhere within the limit of the zone at time of fracturing.

The process of basification and disintegration of the continental crust, regardless of mechanism, unquestionably spreads upwards, and it must overtake the whole thickness of the crust before it is fully completed. In connection with this, it is natural to assume that it is achieved faster when the crust of the earth is thinner. Its progress though, is more difficult, where, owing to the continuing differentiation process, the crust of the earth still grows.

This viewpoint permits clarification of the complex boundary line between the Asiatic continent and the ocean. As is known, the thinnest continental crust appears in the oldest shields, or in median massifs, while it is thickest under young central uplifts appearing in the Alpine intrageosynclines. Its thickness must be relatively greater under the island arcs, not only of the first, but also of the second type, inasmuch as the formation of these arcs is conconnected with the differentiation of the material in the zone of deep-seated fractures.

It is thus natural that the basification process penetrated further to the west, and led to a wide expansion of the ocean in the same direction, in the zone of the Kolym median massif (by which the deep penetration of the Sea of Okhotsk into the continent was conditioned), in the region of the northern, thus the oldest part of the Chinese

shield (Yellow Sea), and within the limits of the Indochina median massif (Gulf of Siam). At the same time, the basification and oceanization processes seem to encompass the geosynclinal upheaval of South Sakhalin, the southern "activated" part of the Chinese shield, the geosynclinal uplifts of Laos and Malay Peninsula (Beloussov, 1956; Khuan, 1952). Blocks of continental crust are also preserved during a certain time, forming island arcs of both types, inasmuch as here the continental crust was thicker, and the process of its thickening continued up to most recent times. From this viewpoint, the newest data, showing that blocks of continental crust forming the bases of island arcs of the first type, wedge out at a certain depth, show good agreement (Butterlin, 1956).

It is known that the seats of deep earthquakes around the Pacific Ocean are distributed, roughly speaking, along certain surfaces, which dip at nearly 60 degrees under the surrounding continents. It is also known, that the deepest foci are located at depths below 700 km. Apparently, these surfaces have a direct relation to the basification. We may assume, that the difference in composition of material under the continents and oceans is not limited to the crust, and takes place at considerably greater depths, penetrating the mantle of the earth by not less than 700 km. But even then, the focal surface may be considered as a zone where a disintegration of the continental mantle, and its replacement by the oceanic takes place (fig. 7).

Inasmuch as the basification is linked with the rising of superheated basaltic masses from deeper zones of the mantle, these must exert upon the upper part of the mantle and the crust not only physicochemical action but also a simple thermal action. They must contribute to melting and the rising of the light material of the mantle and the crust. The possibility that this may be the reason for increase of volcanism around the Pacific Ocean is not excluded. Wherever the continental crust of superheated basaltic masses melts, we see the results of such fusion in the form of andesitic lava effusions at the surface which disintegrates in a later process of denudation. Thus, the mechanism of continental crust transformation may not only consist in metasomatic basification, but also in melting of deep-seated crust layers on the surface with a subsequent erosion and the drifting of their material in the form of fragmental deposits and soluble salts into the ocean.

The appearance of huge granite batholiths in the Cordilleras and in the Andes might perhaps be explained by the same melting process of the superheated deep-seated masses. The age of these batholiths, and the age of the inversion in corresponding geosynclines is mostly Jurassic, thus earlier than the age of inversion and batholiths in other Alpine geosynclines. It is known that the Pacific Ocean region, in this regard, is different from other regions. The inversion is of Jurassic age not only in the eastern, but also in the western periphery of the Pacific Ocean – in the Verkhoyansk and Sikhote Alin geosynclines. The possibility is not excluded that this aspect of Pacific Ocean area development may be linked with the thermal influence of ascending superheated masses of the upper part of the mantle and on the crust of the earth. Their ascension began at the beginning of the Mesozoic, and induced granite fusion and the acceleration of inversion.

The consideration herein developed on the origin of island arcs is a part of more general representations about the evolution of the earth. In the light of these representations the earth is seen to develope through differentiation of matter by way of subsequent melting of relatively easily fusible components, and their displacement upward. At the same time, it is assumed that the earth, having formed in a cold state, is then being heated by mineral radioactivity, and this contributing to the melting of relatively light constituents.

The most intense differentiation in the upper "story" (apparently at depths of 100 to 200 km) determines the geosynclinal conditions. After it exhausts itself, a slower differentiation of a deeper "story" (probably 200 to 300 km) takes place, and this brings about a change from geosynclinal to platform conditions. Further heating activates material of still deeper levels, and provokes the rise of larger basaltic masses toward the surface. Post-platform activation, which reveals itself in Central and East Asia, the plateau-basalt effusion, and finally the disintegration of the continental crust with formation of large grabens, of inland seas and oceans, which gradually expand, all are linked with this rise. The appearance of deep faults in the crust and in the upper part of the mantle, determining the movement of the material, and also the phenomena expressed in the form of periodic heat accumulation in depth, a certain expansion, the opening of deep fractures with a rapid ascent of the heat together with the heated material toward the surface, along the faults, all exert a substantial influence on the development of the tectonic process. The periodicity of tectogenesis may be connected with the latter phenomenon, which may be compared with the kinetics of a boiling teapot.

It is assumed that the earth is still heating up. For that reason those signs of crustal and mantle expansion, which are revealed in the process of ocean-trough formation and widening must be construed as the expression of a more general expansion of the whole crust, and of the upper part of the mantle in an expanding earth as a whole. Concrete materialization of the expansion, in a form of fracture formation and expansion, and of rising of deep-seated material to the surface, may however, be irregular,

embracing certain areas before others, which conditions a simultaneous existence in the crust of the regions of the earth of different stages of development.

The authors accept the idea of a deep-seated origin of ocean water, as formulated in the latest literature (Ronov, 1959; Rubi, 1957; Rubey, 1951), and they assume that water vapors together with other light constituents, originate from the crust and mantle of the earth. Ocean water must be looked upon as a crustal layer of the earth, entering in its composition with rights equal to those of the underlying basalts, and jointly participating in the establishment of an isostatic equilibrium not only with this basalt layer, but also with the upper part of the mantle. This compensation will be examined in more complete form in another work.

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IMPORTANCE OF INCLUSIONS IN MINERALS TO THE THEORY OF ORE GENESIS AND STUDY OF THE MINERAL FORMING MEDIUM[1]

By

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• translated by Eugene A. Alexandrov[2] •

ABSTRACT

Inclusions in minerals constitute evidence of past processes. Three types of inclusions are recognized; solidified, gaseous, and liquid and relations can be drawn between them and the several stages of mineralization - magmatic, pneumatolytic, and hydrothermal. Inclusion thermometry permits analysis of temperature, space, and time relations during mineral-forming processes. -- M. Russell.

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TRENDS IN THE THEORY OF ORE GENESIS

The theories of ore genesis are being tested by studies in three areas: 1) geologic-petrographic, 2) geochemical-mineralogical, 3) experimental. Recent studies of inclusions of mineral-forming fluids have confirmed the results of genetic studies of the deposits. Geologic-petrographic studies stress comprehensive study of mineralizing environments: Facies and geochemical features of ore deposits, depth and distance from a plutonic source, and tectonic and lithologic peculiarites of the deposits. Such studies shed light on basic ore-forming processes. Geochemical-mineralogical studies are concerned with the products of ore formation: Mineral species and varieties, mineral generations, ore structures and textures, and wall rock alteration. These studies make it possible to classify ore deposits and establish regularities in mineral associations.

Experimental studies attempt to reproduce natural minerals under controlled laboratory conditions. They are also concerned with the ability of mineral-forming solutions to transport nonvolatile components. Although artificial crystallization may not exactly duplicate natural processes, it yields important data on the physicochemical behavior of mineral-forming solutions.

Despite these achievements, S.S. Smirnov, an expert in ore genesis, said in 1947 (p. 35) that "those theories are still too imperfect. The keys to our problem are not yet found. When we do find them our old earth will open its treasures." Perhaps important considerations have been overlooked in our studies to date.

Liquid inclusions in a mineral are one important evidence of past processes, "miniature autoclaves" containing relics of ore-forming solutions. It is regrettable that these inclusions were for a long time considered ineffective tools in the precise study of ore genesis, even when used with other methods. Lack of data from inclusion studies resulted in imperfect classification of ore deposits, from which foreign geologists excluded an important group of pneumatolytic deposits.

In Russian literature the term "postmagmatic" is used to include many types of deposits supposedly formed by hydrothermal solutions alone. Few scientists have advocated the importance of pneumatolysis in many of these deposits.

New classifications of ore deposits are based on ore mineralogy and textures, structural environment of mineralization, and morphology of ore bodies. These classifications indicate advances in the descriptive aspects of mineralogy, but also suggest lack of progress in genetic theory of ore deposits.

Although some geologists have suggested the necessity of thorough study of wall rock alteration, the possibility of deducing environment of mineralization from its direct products remains limited. The active solutions from which the minerals were deposited have been considered inaccessible for study. This missing link has pushed mineralogy, especially in foreign countries, from a genetic to a descriptive science. Some mineralogy textbooks have become essentially reference books of physical and crystallochemical properties of minerals, slowly losing important chapters on ore genesis.

In this way, the theory of ore formation lagged further behind the growing knowledge of mineral composition, structure, and properties. As a result, the major achievements in the study of environments of mineralization and ore composition underscored the relatively poor results of genetic studies.

Mineral prospecting is no longer done according to old prospectors' tradition. This is be-

[1] Translated from Znacheniye issledovany vklyucheny v mineralakh dlya teorii rudoobrazovaniya i ucheniya o mineraloobrazuyushchey srede: in Trudy Vsesoyuzny nauchno-issledovatelsky institute p'yezoopticheskogo mineralnoto syrya, Issledovaniya mineraloobruyushchikh rastvorov, v. 1, no. 2, 1957, pp. 9-29.

[2] Columbia University. Edited by Charles M. Schlaudt. Reviewed for technical content by Earl M. Ingerson.

cause of recent experience in the study of geologic and structural environments of mineralization, investigation of wall rock alteration, and solution of some important geochemical and petrologic problems concerning the relation of intrusion to mineralization.

Deeper study of physicochemical conditions of mineral formation, and comparison with products of definite processes in the past, might uncover many new regularities useful in prospecting and evaluation of deposits. Direct reconstruction of the mineral-forming process from available minerals and alteration products is impossible. Even a first approximation requires further evidence in several directions.

Genetic studies based on data from relics of mineralizing solutions have developed rapidly in Soviet science. These relics, hermetically sealed and preserved as solid, liquid, and gaseous inclusions in minerals, were known to scientists long ago. However, systematic and versatile study of these inclusions in minerals was not attempted until about 1950. No methods were developed for the study of the state of mineral-forming solutions, their temperature, pressure, composition and concentration, or pH.

Recently, Soviet scientists have demonstrated the importance of a versatile study of these inclusions in the theory of formation of mineral deposits. Such studies supply additional data to help geologists engaged in the three lines of development mentioned above.

Data from study of inclusions allow correlation of geologic environment with the alteration products of mineral-forming solutions. However, wall rock alteration frequently did not coincide in time with the principal stage of mineralization.

Inclusions may supply data helpful in mineral synthesis and interpretation of mineralizing solutions. The application of laboratory data to interpretation of ore formation, by means of experiments with inclusions, creates an important new basis for the formation of an effective theory of ore formation. Such a theory must make use of all objective data supplied by nature.

USE OF INCLUSIONS FOR THE DETERMINATION OF GENESIS OF MINERALS AND ORE DEPOSITS

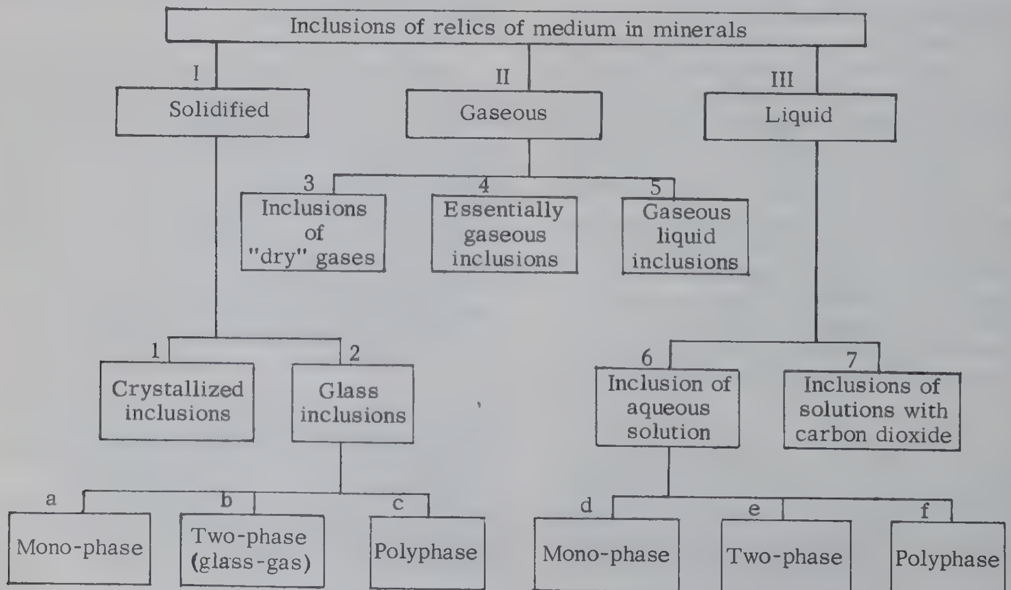
Theories concerning mineralizing fluids are largely based on the many studies of inclusions of these fluids found in minerals. Numerous studies have established that all minerals, during crystallization, capture and preserve drops of the melts and solutions which deposited the mineral. The diverse conditions of mineral formation are indicated by the observed variety of types of inclusions in minerals. These inclusions are clearly divisible into three major groups:

1) Solidified Inclusions, representing drops of melt, from which inclosing minerals were crystallized.

2) Gaseous Inclusions, portions of gaseous, frequently supercritical solutions with low specific density (not carbon dioxide), which caused formation of inclosing minerals.

3) Inclusions of liquid aqueous solutions, of relatively high density, which deposited inclosing minerals at different temperatures.

These major groups clearly characterize different states of depositing media: Melt, gaseous solution, and liquid aqueous solution; which were active, respectively, in magmatic, pneumatolytic, and hydrothermal stages of mineralization.



Scheme of classification of inclusions

The classification diagram shows each group subdivided into types and subtypes, which offer possibilities of more detailed discernment of the physicochemical conditions of mineral formation.

Genetic Importance of Solidified Inclusions

Solidified inclusions in minerals of intrusive rocks are normally crystalline, while those in phenocrysts of extrusive rocks are mainly volcanic glass. In both cases, part of the volume of the inclusions is occupied by small vugs. The spherical form of these inclusions indicates gaseous filling. These inclusions may then present systems of crystals and gas, crystals, or glass and gas.

A drop of melt hermetically isolated within a mineral went through crystallization differentiation during slow cooling at depth. From this melt solid phases were formed and a gaseous phase was isolated. The ratio of solid to gaseous phases in a sealed inclusion evidently reflects the ratio of a given molten magma chamber to the solidified intrusive which formed in the chamber after the escape of an enormous amount of volatile material. In some solidified inclusions in the quartz of granites from the Northern Caucasus, the volume occupied by a gas phase reaches 20 percent. In crystalline-gaseous inclusions of residual melt in pegmatites of Volhynia, the gaseous phase appreciably exceeds this figure in some cases.

Simple observations and measurements of this sort do not yet allow speculation about the quantitative content of non-volatiles and volatiles in magma.

D. S. Belyankin (1947) indicated that chemical analyses of magmatic rocks merely indicate magma composition after the escape of most volatiles. Careful analyses of the chemical composition of solidified inclusions will allow in the future an approach to the solution of the problem of magma composition, as will experiments on the solubility of volatiles in synthetic silicate melts.

Scattered data on solid inclusions in quartz from granites from various depths show differences in the completeness of crystallization of substances in the inclusions. This may provide in the future a useful clue to the approximate depth of formation of an intrusive.

Inclusions of volcanic glass in minerals are commonly polyphase and two-phase, seldom mono-phase. They are characteristic of phenocrysts in extrusive rocks, indicating different cooling rates of inclosed melt and surrounding mineral. Polyphase inclusions were formed in minerals which began to crystallize as the magma rose toward the surface. The presence of one or a few crystalline phases in inclusions within volcanic phenocrysts indicates an incomplete crystallization differentiation during slow cooling of the extrusive. The remaining mass in the inclusion solidified as glass, from which bubbles of gas separated. In two-phase and mono-phase inclusions, crystallization has been prevented due to rapid cooling of the lava at the surface.

If the entire group of solidified inclusions indicate a volcanic origin for the inclosing minerals, then the types of glass inclusions evidently represent slow effusion of lava or rapid volcanic eruptions.

It must be remembered that the solidified inclusions discussed here differ from those solid inclusions which represent fragments of minerals formed simultaneously or prior to the formation of the inclosing inclosing mineral.

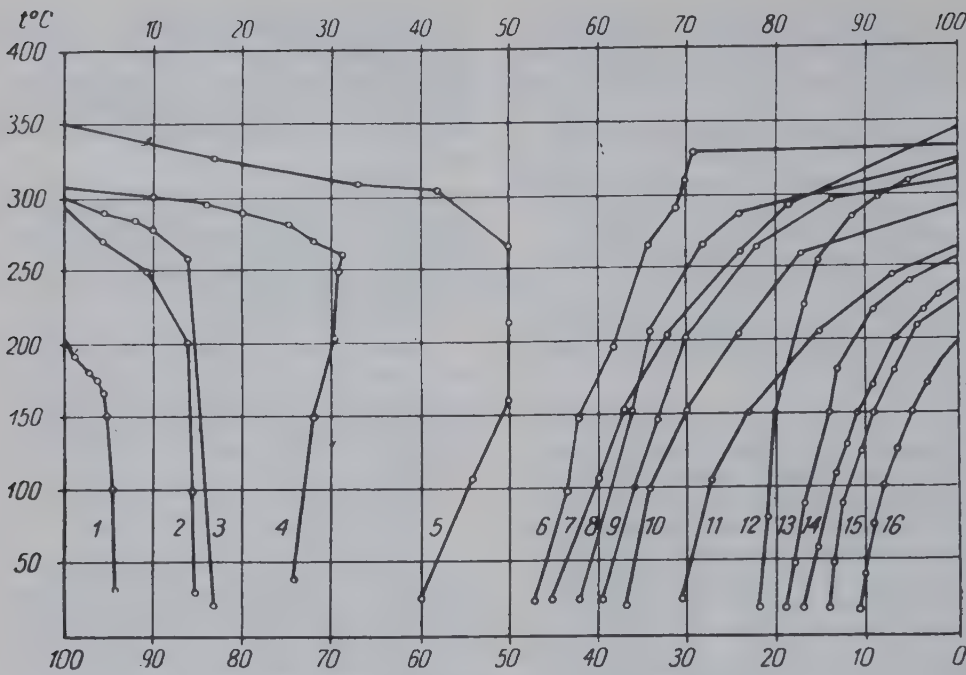
The Genetic Importance of Gaseous Inclusions in Minerals

Our investigations of numerous minerals from postmagmatic deposits show that only gaseous inclusions of the mother liquor or fluid inclusions of aqueous solutions are syngenetic. Gaseous inclusions are those in which the gaseous phase occupies most of the volume at room temperature. Liquid inclusions are those in which liquid dominates at room temperature. Also inclusions of CO_2 and mixed inclusions (CO_2 and liquid) are sometimes observed. These may be found in minerals of various origin, but cannot be used for inclusion thermometry or conclusions about the state of mineralizing solutions. These inclusions, as well as inclusions of bituminous substances, are at least partly alien to the mineral, and of little interest for genetic conclusions.

Syngenetic gaseous inclusions were found to be characteristic of most minerals in skarns, greisens, pegmatite veins, deposits formed near an intrusion, and in minerals deposited by sublimation during volcanic eruptions.

Gaseous inclusions may be divided into three types (figure 1) according to the degree of filling of the vacuole by the gaseous phase at room temperature, and according to their behavior during heating: 1) inclusions of dry gases, which contain little or no liquid phase; 2) substantially gaseous inclusions, which contain less than 25 percent liquid by volume; 3) gaseous liquid inclusions, where liquid occupies 25 to 50 percent of the volume (inclusions of this type homogenize at the inversion point).

The relative volume of solid phases deposited on the walls of the vacuole from the fluid increases from the first to second type of inclusion listed above. Large amounts of minerals deposited in gaseous-liquid inclusions of topaz and quartz from Volynya indicate multicomponent composition of supercritical solutions,



Percent of filling of inclusions by gaseous phase

FIGURE 1. The course of homogenization of gaseous and liquid inclusions in pneumatolytic and hydrothermal quartz from different deposits

1-5 - II-type of homogenization.

6-16 - I-type of homogenization

Subtypes of homogenization

4-5 - homogenization of inversion point

6,8 - homogenization at boiling point

12 - homogenization of polyphase inclusion

and considerable capacity of the solutions to transport nonvolatiles in the form of metasilicates of sodium and potassium, chlorides, and fluorides.

Heterogeneous systems in type of inclusion characteristically homogenize to a gaseous phase as in Type II, but the course of their homogenization is different (fig. 1). The specific density of these solutions (at constant volume in vacuoles) was below the critical density of usual liquid solutions. Whether they are called solutions of relatively low-density fluids, or supercritical solutions, they have the tendency to expand indefinitely when confining pressure is released. This is not a property of liquids. In the case of gaseous-liquid inclusions, the solutions are not ideal gases with inherent maximum freedom of atoms, ions, and molecules. Cohesive forces of particles need not correspond to the liquid state in solutions of low density and high specific volume.

It is easy to imagine a liquid such as pure water entirely filling an autoclave at room temperature. Heating the autoclave above 373°C will not reduce density, and specific volume will remain low, behavior not inherent to the gaseous state. Therefore, in discussions about determination of what is gas or liquid, particularly with regard to distinction of hydrothermal and pneumatolytic minerals, the main consideration is not temperature or pressure, but rather solution density and specific volume.

If, during heating, the inclusion is filled by a liquid phase, by following the corresponding isochore on the PT diagram (depending on pressure) we will arrive at a point located above the critical temperature, and the inclusion will contain liquid in a supercritical state. Careful studies have shown that no phase transformation occurs inside inclusions during heating through critical temperature. Also, there is no sharp difference in liquid properties above and below critical temperature.

In an inclusion which homogenizes to a gaseous phase, we will have "gas" in a supercritical state at high temperatures. Consequently all differences are in the difference of densities.

Such reasoning should not serve as a basis for complete comparison of liquid properties below and above the critical point. A smooth

temperature change in the liquid phase (at constant volume) results in a gradual change of phase properties. The gradual character of the process probably depends on the different degrees of order of the structural units of liquid, which in turn depend on thermodynamic properties.

If the distinction between liquid melt, dominated by nonvolatile components, and aqueous solutions, dominated by volatiles, were lost, magmatic and hydrothermal minerals could not be distinguished. This would lead to exclusion of genetic classifications of deposits; and renouncing of established ideas which have proved successful in prospecting and exploration.

Syngenetic inclusions, which homogenize to a gaseous phase with a density below critical, are usually reliable indicators of crystallization from a gaseous phase. In other words, they indicate a pneumatolytic origin of the inclosing minerals. Different homogenization behavior for the three types of gaseous inclusions may lead to distinction among early, late, and last stage pneumatolysis. Analyses of these inclusions will make possible conclusions about the composition of emanations from magma chambers. Such emanations are responsible for practically every important greisen, pegmatite, and skarn deposit, as well as many other types.

The Genetic Importance of Liquid Inclusions in Minerals

Inclusions of liquid aqueous solutions, which crystallized or healed minerals under conditions of hydrothermal and cold-water ore formation are observed at room temperature in the form of homogeneous or heterogeneous systems. Cooling from the warm solution temperature to room temperature favored reduction of liquid volume in the inclusion, and formation of a vacuum and gas phase in its place, with the gas occupying less than one-half of the vacuole volume. During cooling, the solution may become supersaturated with respect to one or more dissolved species, in which case crystallization will occur on the walls of the vacuole, forming a polyphase inclusion. If the solution is inclosed at fairly low temperature, the vapor phase may not evolve in cooling to ambient temperature.

Polyphase, two-phase, and monophase inclusions can be distinguished among the inclusions of aqueous solutions. Each type is important to genetic conclusions.

Homogenization of these inclusions through heating results in a liquid phase, indicating high density and low specific volumes of the inclosed solutions; this indicates a hydrothermal origin. In some liquid inclusions with relatively low density near the point of homogenization, continuous boiling is noted (see figure 1, curves 6 and 8). This confirms the possibility of such phenomena in natural hydrothermal activity. Mono-phase liquid inclusions, as indicated by studies of artificial crystallization, are evidence of crystal growth from solutions below 40-50°C. Theoretically, solutions inclosed at 200°C may remain monophase, but only if burial occurred at pressures around 3,000 atmospheres, a geologic improbability in these cases.

Liquid inclusions apparently remain monophase in minerals formed on the earth's surface, or in the last stages of shallow hydrothermal mineralization. Anomalous two-phase inclusions may form in such minerals if the host mineral is extremely soluble in aqueous solutions.

Syngenetic liquid aqueous inclusions which are heterogeneous at room temperature generally indicate a hydrothermal origin for the inclosing mineral.

The key to distinguishing the genesis for minerals according to inclusions (table 1) has been widely used recently during studies of pegmatites, skarn, pneumatolytic, hydrothermal, and cold-water deposits of metallic minerals. Application of this recently-improved key, in combination with geologic-petrographic, mineralogical-geochemical methods and methods of mineralogical thermometry, allows us to create a classification of postmagmatic mineral deposits, and sheds light on many minor details involved in a realistic theory of ore genesis.

IMPORTANCE OF THERMOMETRIC ANALYSIS OF MINERALS AND DETERMINATION OF RELATIVE TEMPERATURES OF MINERAL FORMATION BY USE OF INCLUSIONS OF AQUEOUS SOLUTIONS

Temperature was long ago recognized as one of the most important factors in mineral formation and used in the genetic classification of hydrothermal deposits. Paragenetic relationships, reflecting very approximately temperatures of the process, served as a basis for separation of these deposits into hypothermal, mesothermal, and epithermal. Attempts to determine exact temperatures from these relationships have met insurmountable difficulties.

Introduction of pressure corrections to homogenization temperatures of liquid inclusions offers inviting solutions for the problem of determining mineralizing temperatures. It is, however, just as important to establish the relative course of temperature of mineralization in space and time. These changes may be determined by differences in homogenization temperatures in minerals from all parts and stages of the deposit. This is the aim of inclusion thermometry, which has been successfully

TABLE 1. Key for determination of genesis of minerals according to inclusions of mineral-forming media (Exhibit in Hall No. 8 of the Earth Science Museum on the 27th floor of the Moscow University)

Characteristics of inclusions at room temperature		Characteristics of inclusions at: higher temperature and in the process of heating		Genetic meaning of inclusions	
According to physical condition of filling	According to the observed phases and their volumetric ratio	Types and subtypes of homogenization	State of inclosed medium after homogenization	Primary condition of the mineral forming medium	Origin of minerals
Solidified		I. Melting		Magmatic melts	Magmatic
Crystallized	C; C+G		Melt	Deep-seated intrusions.	Minerals of intrusives.
Crystalline-gaseous	C>1/2+G<1/2+L	Gradual liquefaction	Residual melt	Pegmatites	Minerals of primary zone of pegmatites
Amorphous	Vg; Vg+G; Vg+G+C		Melt	Lava effusives	Minerals of effusives.
Gaseous		II. Disappearance of liquid phase		Gaseous solutions	Pneumatolytic
Dry gases	G+L<10 percent	Rapid transformation of liquid into gas	Gas	Gases (vapors) of very low density	Minerals of sublimates.
Substantially gaseous	G>3/4+L<1/4	Gradual transformation of liquid to gas	Gas	Gases of low density, frequently supercritical	Early pneumatolytic minerals and metasomes of pegmatites, skarns, and greisens
Gaseous-liquid	G (from 1/2 to 3/4) +L (from 1/2 to 1/4)	Transformation at inversion point	Fluid (F)	Gases of supercritical medium density	Late pneumatolytic minerals and metasomes of pegmatites, skarns, and greisens
Liquid-gaseous	G>1/2+L<1/2+C	Transformation at the critical point or boiling point	Fluid (F)	Dense gases near the critical value of specific volumes, temperatures and pressures	
Liquid		III. Disappearance of gaseous phase		Liquid solutions	Hydrothermal
Polyphase	L>1/2+G<1/2+C	With solution of solid phases and disappearance of vapor bubbles	Liquid	High temperature hydrotherms supersaturated with haloids	Early hydrothermal
Two-phase	L>1/2+G<1/2	With gradual disappearance of vapor bubbles	Liquid	Diluted epithermal and mesothermal waters	Late hydrothermal
Mono-phase	L			Warm and cold juvenile and meteoric waters	Minerals deposited in cold water

C - crystals of inclosed minerals, Vg - volcanic glass, G - gas (vapor), L - liquid solution, F - fluid (state of medium with density intermediate between liquid and gas). The figures indicate the ratio of phase volumes at room temperature within volume of vug occupied by the inclusion.

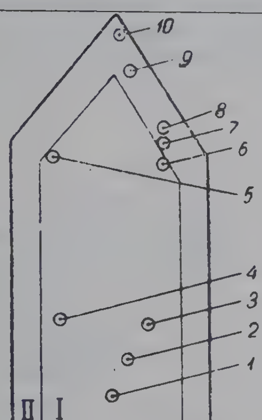
applied to many deposits. This analysis consists of consecutive determination of temperature of homogenization of normal liquid inclusions from different zones of crystal growth, different generations and paragenetic association.

The simplest example of such a study in time is represented by Table 2. Constant decline of temperature during the process of crystal growth was established for this study by inclusion thermometry.

Figure 2 represents data recorded by V. F. Lesnyak relative to temperature change in various stages of formation of the hydrothermal lead-zinc deposits of Sadon and Zgid.

The curves in Figure 3 illustrate the cooling of hydrothermal solutions as they move upward. These curves were plotted considering present topography and average homogenization temperatures of inclusions in sphalerite. Curve 1 relates to deposition of brown sphalerite of the second stage of mineralization, Curve 2 of the deposition of light brown sphalerite of the third

TABLE 2. Temperature change of solutions during growth of quartz crystals

Schematic sequence of zones of quartz crystal	Number of zone	Points of measurement	Temperature of homogenization of primary inclusions, °C	Type of homogenization
		1	255	
		2	252	
	I	3	250	I
		4	224	
		5	215	
		6	185	
		7	168	
	II	8	168	I
		9	152	
		10	118	

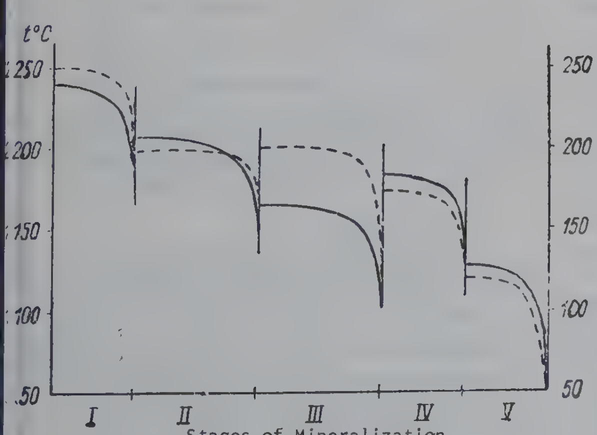


FIGURE 2. Curves of temperature regime of process of mineral formation of base metals deposits (after V.F. Lesnyak).

—— 1 - curve of temperature regime of mineral-forming solutions at the deposit of Sadon;

--- 2 - curve of temperature regime of mineral-forming solutions of the Zgid deposit.

| 3 - tectonic movements

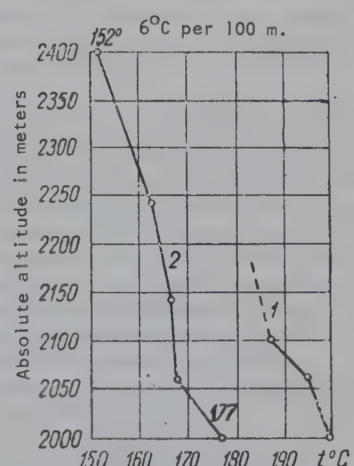


FIGURE 3. Rate of cooling of ore-forming hydrothermal solutions under conditions of upward movement of solution (according to sphalerite from deposit of Sadon)

1 - brown sphalerite of the II-stage of mineralization;

2 - light brown sphalerite of the III-stage of mineralization.

stage of mineralization at varying depths. This curve shows that at the 2, 000 meter level, crystallization of sphalerite occurred at an average minimum temperature of of 177°C, while sphalerite of the same generation at the 2, 400 meter level indicated a temperature of 152°C. Here the rate of cooling of the rising solutions was about 6°C per 100 meters.

These simple examples illustrate the application of inclusion thermometry for determining temperature change in time and space, and consequently, other related physicochemical parameters of the mineralizing process.

Different temperatures of homogenization of normal liquid inclusions reflect differences in specific gravity of included solutions, related physicochemical parameters, and, most important, the temperature of the process in an open, or almost open, system. It is interesting to note that under conditions of synthetic hydrothermal growth of quartz and other minerals in an autoclave, the temperature of homogenization of liquid inclusions in different zones of growth of the same crystal is approximately the same. (Butuzov and Ikornikova, 1955).

This requires particular examination. Synthetic minerals are grown in hermetically closed systems, in contrast to natural conditions. The specific volume (or density) of the inclosed solution is determined by the coefficient of autoclave filling, and remains essentially constant regardless of pressure or temperature variations. Homogenization temperatures throughout the crystal will be the same, but true temperature, if changes after the moment of "homogenization" of autoclave content, must be determined by the introduction of pressure corrections.

Under natural conditions the volume of hydrothermal solutions, filling some natural reservoir in which crystallization takes place (e. g., a rock crystal cavity), is changeable and a function of temperature, since permeable surrounding rocks reduce the importance of pressure. It is easy to imagine such a natural autoclave at the beginning of crystallization of quartz, entirely filled with a solution at 320°C, and the same space in a later growth stage entirely filled with a solution at 100°C. Naturally the densities of the solutions, at constant concentrations, will be different in the two cases. Inclusions corresponding to these cases, which formed in different zones of crystal growth, will demonstrate at room temperature different ratios of liquid volume to gas bubble volume. These ratios in this case might be 35 percent gas for the former case, 5 percent for the latter.

Homogenization temperatures of such inclusions will depend on solution density, which in turn is a function of temperature of crystallization. In this way, the course of temperature changes during crystallization will be reflected by homogenization temperatures. Relative temperature of the natural process is established by these temperatures.

These temperatures are most important in the dynamics of mineral formation. Consider for the moment that minimum and relative temperative values of natural processes are the important contributions of inclusion thermometry.

The temperature scale adopted for use at the earth's surface naturally is difficult to coordinate with temperatures of deep-seated processes because of the sharp differences in pressure and solution concentration, as well as the impossibility of direct measurement.

Temperatures of homogenization of liquid inclusions depart more and more from true formation temperatures with increasing pressure and solution concentration, as seen in Figure 4.

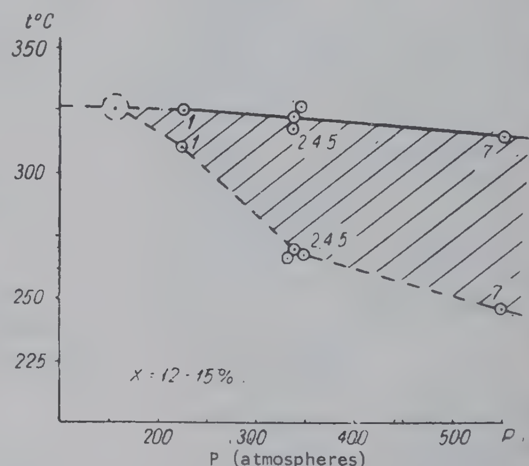


FIGURE 4. Divergence between the true temperatures of hydrothermal crystallization of quartz and temperatures of homogenization of inclusions in quartz, as a function of pressure.

1 - true temperature.
2 - temperature of homogenization.
3 - points of measurements and the region of temperature divergence.

Determination of true temperatures of formation from homogenization temperatures requires much tedious work to establish pressure corrections and corrections for solution concentration. We are, however, interested in relative temperatures and the course of temperature change throughout deposition. At present, we must accept the homogenization temperatures as the best available relative values.

The biostratigraphic method of relative geochronology is of great importance in the development of geology. The method of radioactive dating, though a more direct guide to

absolute ages of rocks, did not substantially reduce the importance of the relative chronology.

In necessary and possible cases, relative and absolute time scales have been connected by the new methods. Relative temperatures determined by homogenization of inclusions likewise need to be replaced by absolute values. Attempts to request an absolute precision from inclusion thermometry without understanding the nature of the homogenization temperature are quite strange. One should not forget that introduction of measures and numbers into the geology of processes developing at great depth is connected with great difficulties.

One should not underestimate the importance of relative measurements as indications of the course of evolution of natural processes. This process of determining temperatures as a key to mineral genesis is of such importance to economic geology that it may be compared only with the determination of relative ages of strata in geology.

Changes in homogenization temperatures of syngenetic inclusions allow:

1) Determination of the course of temperature changes in different minerals and deposits;

2) determination of the relative time of formation of various minerals and zones in complex deposits;

3) establishment of the dependence of some physical properties and habits of minerals on temperature changes; and

4) objective determination of high-, middle-, and low-temperature mineral generations and deposits. On the basis of homogenization temperatures in hydrothermal minerals, the following scale may be accepted. High temperature – 500°-350°C, medium temperature – 350°-200°C, low temperature – 200°-50°C, and cold water –below 50°C.

Here the superposition of low temperature mineralization on higher temperature mineralization should be considered. It is also notable that inclusion thermometry sometimes discloses cases of high temperature minerals superposed on lower temperature minerals.

THE ACTIVITY OF MINERALIZING SOLUTIONS IN TIME AND SPACE

Long experience in the study of inclusions in minerals allows some comment on the activity of mineralizing solutions in time and space, those "circulating juices of the earth" discussed by Al Biruni and Agricola.

The major role assigned to the mineralizing medium in Russian and foreign literature is not matched by understanding of this medium. The rocks inclosing a site of mineralization, with all their peculiarities of chemical composition, porosity, temperature, lithostatic pressure, and other factors, constitute an environment for mineralization. The magmatic solutions represent very active natural systems interacting with the surrounding rocks. These active systems may be characterized by the interrelated parameters T-P-C, variations in which direct the course of mineralization.

This physico-chemical parameters change constantly with highly mobile solutions, or in rare cases of systems essentially at rest (vugs, miarolitic cavities) are in stable equilibrium.

These active solutions are the most important factor in mineral formation. It is impossible to study any crystalline substance with relation to the processes of its formation, without relation to the liquid or gas, during whose change in character or movement this substance was formed. The equilibrium arrangement of atoms in a crystalline substance is definitely dependent on the surrounding physicochemical environment. As these conditions constantly change, the character of equilibrium must also change or even cease to exist (Dolivo-Dobrovolsky, 1937).

Hermetically isolated inclusions of mineralizing fluids are invaluable clues to the physicochemical conditions of each moment of crystallization of the mineral.

Intrusives seen today often represent locations of former magma chambers where silicate melts underwent complex processes of chemical interaction of atoms and molecules at high temperatures and pressures. These processes directly resulted in crystallization of intrusive rocks, formation of plutonic bodies, and origin of magmatic mineral deposits. They were also involved in a constant distillation and removal of volatiles in the form of supercritical gases into the surrounding rocks. The mineral-forming substances in such solutions are distillates, sodium and potassium metasilicates, easily volatile heavy metal chlorides and fluorides, and complex hydrated compounds. These gaseous emanations, a logical product of magmatic differentiation and assimilation of material from surrounding rocks during their movement from the magma chamber, created a highly active natural system of pneumatolytic mineralization. Exceptionally mobile, superheated high-pressure gas streams intensively attacked the rock along the main channels of movement. Rocks altered by pneumatolytic solutions are often of great bulk. Usually the products of deposition from these solutions were localized in the areas of most intense flow, such as faults and fractures.

Pneumatolytic mineralization took place in essentially open systems rapidly changing with time. The character of mineralization depended on the stage of development of the source magma

chamber and on the surrounding rocks reacting with the gas stream.

As these solutions coursed away from the magma chamber, their aggregate state changed with space and time. Finally, pneumatolytic solutions became hydrothermal solutions.

Transformation of the aggregate state of the solution resulted in changes in composition, texture, and paragenesis of the deposited minerals. The activity of the solutions was considerably reduced, reducing the amount and intensity of wall rock alteration. Wall rock alteration has been shown to be far from syngenetic with the productive stage of mineralization. As the magma chamber began to cool and differentiation progressed, the locus of the boundary between supercritical and subcritical conditions moved deeper into the earth. Here complex polygenetic ore deposits are found, showing generations of successively lower temperature minerals. True hydrothermal deposits are found above the uppermost level of penetration of supercritical fluids.

Above the magma chamber and below this mobile activity-boundary between supercritical and subcritical conditions, pneumatolytic deposits formed from time to time. They were usually associated with a cessation of emanations from the magma chamber, due to plugging of channels or rapid formation of the intrusive. Sometimes this mobile boundary even went into the old magma chamber, causing deposition of hydrothermal minerals in the chamber itself. In such cases, skarns formed at the contacts, greisens in the alteration halo of the intrusives, pegmatites, and purely pneumatolytic deposits were transformed by a superposed hydrothermal mineral formation. For example, polygenetic pegmatite bodies of magmatic, pneumatolytic and hydrothermal origin could be formed.

It is, naturally, impossible to demonstrate the entire complex variability of hypogene mineral formation in one paper. The above merely represents a very general scheme which could be broken by any of several changes in the system. A sudden pressure reduction due to opening of channels above could cause hydrothermal solutions to be transformed to gaseous pneumatolytic fluids.

The period of magmatic activity of any pluton can be broken into a number of shorter segments of time characterized by definite aggregate states of solutions and peculiar P-T-C relationships. These segments may be called stages, levels, and sub-levels in the process of mineral formation (Yermakov, 1950). They are represented in space and time of zones in pegmatites and various mineral generations in ore deposits. These zones and generations reveal the changing character of activity through studies of inclusions of the mineralizing solutions.

Three stages of magmatic activity are characterized by definite conditions of the mineral-forming medium:

1) Liquid residual silicate melt, which formed the igneous minerals;
2) gaseous solutions, which deposited the pneumatolytic minerals; and
3) liquid aqueous solutions, which deposited hydrothermal minerals. Ideas about the genetic history of the deposit must be based on these definite gradations in the mineralizing process.

The stage of mineralization is a major part of the process as a whole, characterized for a given place and time of deposition by an equal aggregate state of the active solutions.

A definite mineral association, produced by variations in the physicochemical parameters without a change in aggregate state of the solution, is typical of the level of mineralization, a subdivision of the stage. Within a definite environment, the level is frequently separated from another level by tectonic displacements.

The sublevel of mineralization is part of a level, and differs from other sublevels by a more or less sharp change of temperature, pressure, composition, or solution concentration, which cause interruptions in mineral formation and solution of previously deposited minerals.

Lack of objective criteria for distinguishing minerals formed from media of specific states retarded the evolution of theories of ore genesis. Inclusions provided the keys to distinguish minerals according to the state of the parent solution and to early and late stages and levels. Changes in types and subtypes of homogenization during heating, variations in homogenization temperatures, and variations in composition and concentration of solutions are useful evidences of the mineralizing process.

These inclusions allow us to draw the genetic birth certificate of the inclosing mineral and to follow its history since formation. Inclusions in minerals in the country rock reveal the effect of solutions on their environment. Further extension of these studies leads to detailed information about the manner of transportation of mineral-forming material; and this eventually leads to discovery of the regularities of distribution and alteration of mineralization in space, knowledge of which is necessary for prospecting and evaluation of deposits at depth.

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THREE TYPES OF PLASTIC DEFORMATION IN GALENA[1]

By

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• translated by Royer and Roger, Inc. •

ABSTRACT

The aim of the article is to give a characteristic of plastic deformations of galena in nature. Under the action of pressure galena deforms plastically by gliding, mechanical twinning and polygonisation. Each deformation process is examined on the basis of a dislocational mechanism, taking into consideration observations in nature and data of experiments. -- Auth. English summ.

* * *

INTRODUCTION

Mechanical deformations of minerals are very widespread in nature: the overwhelming majority of the minerals investigated by the present writer have shown deformations on one scale or another.

The mechanism of deformation of minerals plays a very important role in their genetic history. In many cases, deformations control the origin of the minerals by opening paths for the mineral-forming solutions, and frequently the chemical reactions in the formation and transformation of minerals begin and end at the "command", so-to-speak, of the deforming forces.

From the practical point of view the deformations, apart from their important role in the origin of minerals, particularly as industrial raw material, also attract attention when they have the opposite significance -- they produce technical defects, as in such economically important minerals as mica, asbestos, piezoelectric quartz, Iceland spar and precious gems, so that some part of the minerals that are formed must be lost and the entire deposit may even lose its industrial value if such defects make the mineral unsuitable for practical use. At the same time, mechanical deformations sometimes play a positive role, by taking direct part in the production of useful properties of certain minerals such as gemstones and minerals suitable for carving: jaspers acquire beautiful patterns, and the net of fractures in the matrix are filled with light-colored material.

In spite of their widespread distribution and their genetic and practical importance, mechanical deformations of minerals unfortunately have not attracted enough attention on the part of geologists. They are almost completely ignored in textbooks, and if they are mentioned it is only in passing without analysis. The same may be said of the greater part of scientific publications. This is a natural consequence of that viewpoint in mineralogy which limits its scope as a science to only one aspect of the problem, the genesis of minerals, assuming that "mineralogy is the chemistry of the earth's crust", that the genesis of minerals is only "a chemical process", etc. The result is that another extremely important aspect of mineralogy -- the physical -- is excluded from the scope of mineralogists' interests. Nevertheless it is becoming clear at the present time that mineralogy must simultaneously be both the chemistry and the physics of minerals and of the processes of mineralization, and its tasks include the history of minerals as a whole, in all of its various aspects (Grigor'yev, Vernadskiy et al., 1955).

In spite of this state of affairs, however, there are valuable papers devoted to the mechanical deformations of minerals. One may, for example, mention the important paper by V. I. Vernadskiy (1897) on slip in mineral crystals; the very thorough survey with its original data by O. Muegge (1898); the brief review by L. J. Spencer (1922);[3] the review of deformations in ore minerals made by B. Ramdohr (1955) and many other papers on particular problems. Numerous experiments in the mechanical deformation of mineral crystals, which have contributed to the knowledge of such occurrences in nature, have been considered, in addition to the above-mentioned papers, in publications by K. Veit (1922), M. J. Buerger (1928, 1930) G. D. Gogoberidze (1952), in the expansive anthology by V. D. Kuznetsov (1941) and in other books on the physics of crystals, as well as in articles in learned journals. The "System of Mineralogy"

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[1]Translated from Tri tipa plasticheskikh deformatsiy galenta: Mineralogicheskiy sbornik, L'vovskogo geologicheskogo obshchestva, no. 12, pp. 129-143, Izdatelstvo L'vovskogo Universiteta, 1958.

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[3]In addition to deformed crystals, L. J. Spencer has also considered curved forms of growth.

by a group of American authors (Dana et al., 1954) contains data on slip and mechanical twinning in minerals. There are tables of elements in mechanical deformations and the constant related to them (Birch et al., 1949).

Some attention has been given by petrographers to mechanical deformations of minerals in connection with their study of dynamic metamorphism, since in explaining the structures of rocks they must consider the peculiar features of the minerals that compose them. Textbooks on petrography, for example the recently issued book by N. A. Yeliseyev (1953), contain a certain amount of information on the mechanical deformation of crystals. Special works have been published on the study of deformed rocks and minerals, among which the best known in the Soviet Union are those of A. V. Pek (1939), and of Kh. V. Fernbern (1949). It must be admitted that in this respect mineralogy appears to have fallen behind petrography.

An understanding of the deformation of minerals in nature, which are unusually varied in both occurrence and scale, first of all requires discovering and studying those very simple, elementary phenomena of deformations whose combinations result in the endless changes in form occurring in nature. Only by knowing such elementary phenomena is it possible to make calculations of the complex -- that is, compound -- processes, naturally taking account of the specific features of the latter. A consideration of the elements of deformation should immediately be introduced into textbooks and reference works on mineralogy.

An extremely useful object for showing these mechanical deformations of various types is the well-known and very wide-spread mineral, galena. It is characterized particularly by plastic deformations, on which the present writer is concentrating his attentions, for the time being omitting any consideration of other deformations of the mineral, such as elastic and brittle. It should be noted that, as far as this writer knows, the literature thus far contains no discussions of natural deformations in galena within the scope of his present interest.

It should also be stressed that the purpose of this article is to examine deformations of this mineral in nature, and not merely to present a discussion of a part of the physics of solid bodies; but general theoretical material will be cited as simply and as briefly as possible (using as sources the book by Ye. Shmidt and V. Boas, 1938; A. V. Shubnikov, Ye. Ye. Flint and G. D. Bokiy, 1940; V. D. Kuznetsov, 1941; A. H. Cottrell, 1953; A. Nadai, 1954), and such material will be presented without special references.

It will be apparent that in considering mechanical deformations the minerals must be treated as definite bodies -- mineral units and their aggregates -- and that the mineral forms or species will remain unchanged as chemical substances during the course of a process which is not accompanied by corresponding reactions. Thus mechanical deformations belong to that part of the genetic history of minerals that is called the ontogeny of minerals (Grigor'yev 1955, 1956).

PLASTIC FLOW IN GALENA

Plastic deformations, it is well known, are those changes in the shape of a body which are not accompanied by rupture and which are retained after the action of the deforming forces has ceased.

Among all the varied and complex cases of plastic flow, we may now distinguish the simple phenomena that compose them: 1) slip, 2) twinning and 3) polygonization.

Slip

Slip is a displacement of the layers of a crystal by the application of a force, not accompanied by any rupture of the object's continuity and subordinated to the elements of slip: the slip plane T and the direction of slip t. The slip plane is always some major face of the crystal, and the direction of slip always corresponds to some major edge of the crystal. In slip the particles of the crystal are displaced by distances corresponding to the short interatomic intervals, and retain their mutually parallel orientation.

The kinetics of the process of slip cannot be explained as simply as would appear from the purely geometrical aspects of the phenomenon – as if in the crystal there were a displacement of an entire layer of atoms relative to another -- since in this case the magnitude of the forces would have to be very great, and all the experimental determinations produce values some thousands of times smaller. At the present time the kinetics of slip are explained (on models) on the basis of concepts of dislocation within the crystal.

Dislocations, which are also called displacements or engagements, are disruptions in the arrangement of the atoms of the crystals due either to the presence of one excess atom or to the absence of some atom in the structure. In other words, a dislocation is a local crowding or thinning out of the atoms in the structure. Around the dislocations are created discrepancies in the structure which spread to several adjacent atoms next to the dislocation and then gradually die out.

In this concept, slip takes place in such a manner that within the crystal, a force applied

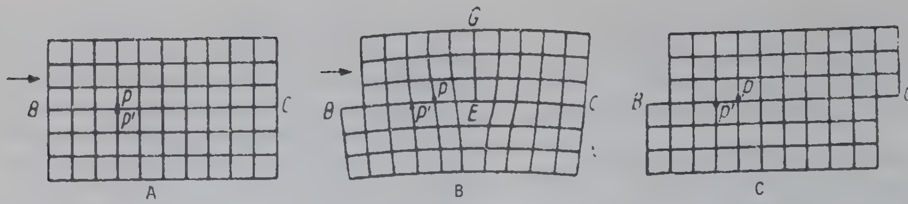


FIGURE 1. Diagram of slip mechanism through the appearance and displacement of a wedge dislocation

BC - plane of displacement of the layers, in which points P and P' diverge
GE - dislocation "wedge".

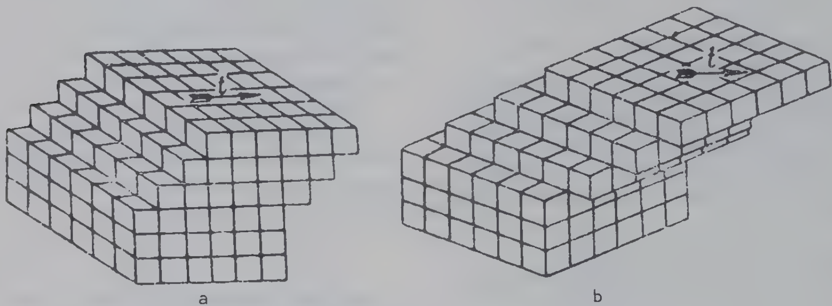


FIGURE 2. Diagram of slip in a cubic crystal with elements

a - T (100) and [100]; b - T (100) and t [110].

to some layer of atoms causes displacement, with the formation of a dislocation (as shown by the diagram in fig. 1), so that the dislocation gradually moves through the crystal and "emerges" from the crystal at the other side; as a result, one part of the crystal is displaced -- moved -- relative to the other part. This movement or dislocation, as a narrowly local process, requires much less force than would be necessary for the movement of a layer of atoms as a whole.

Mineralogical observations have revealed slip in a considerable number of minerals, and if one also takes account of the data from experiments (showing what might be expected in nature) the list of minerals in which slip occurred ranges throughout the entire classification of minerals.

In the case of galena, experiments have revealed slip with the elements T (100) and t [100] and also slip with the elements T (100) and t [110]. These two types of slip are shown by the diagrams in Figure 2. [Read { } for ( ) in all crystal notations in this paper -- Ed.] The slip deformation of galena is revealed in experiments by observation of its results, the slip lines. Such lines are visible on the cleavage surfaces with a hand lens or microscope.

The best developed slip lines in nature may be seen on the large-grained galena from Mina Negrilla, Mexico (Mining Museum, specimen No. 75, 126), which shows fresh, shiny surfaces of cubic cleavage (fig. 3); in addition to slip, this galena has undergone slight polygonization.

Here the slip lines are found on all the surfaces of the cube, parallel to each edge of the cube. Consequently the (100) faces emerge as the slip plane T. As regards determining the direction of slip, t may be most simply determined by observing the deformation of the regularly formed crystals (see fig. 2). When only cleavage fragments are available, the problem is complicated and may at the present time be solved only in particular cases.

M. J. Buerger (1928), in experimenting with galena, came to the very interesting conclusion that in slip along one of the faces of the cube, in the directions [100] and [110], the slip lines on the cubic crystals and surfaces of cubic cleavage develop differently. In slip along [100] (fig. 4a, b) the slip lines appear only on the faces or surfaces perpendicular to both T and t; on the others, parallel to t, slip lines do not appear. If slip takes place along (110), the slip lines will develop on all the faces perpendicular to T (fig. 4c, d). From the simple geometrical relationships it is easy to derive cases in which, according to the distribution and orientation of the slip line on the faces of the cube or surfaces of the cleavage fragments of galena, one may distinguish one type of slip from another, and in some cases even determine a combination of slip along [100] and [110].

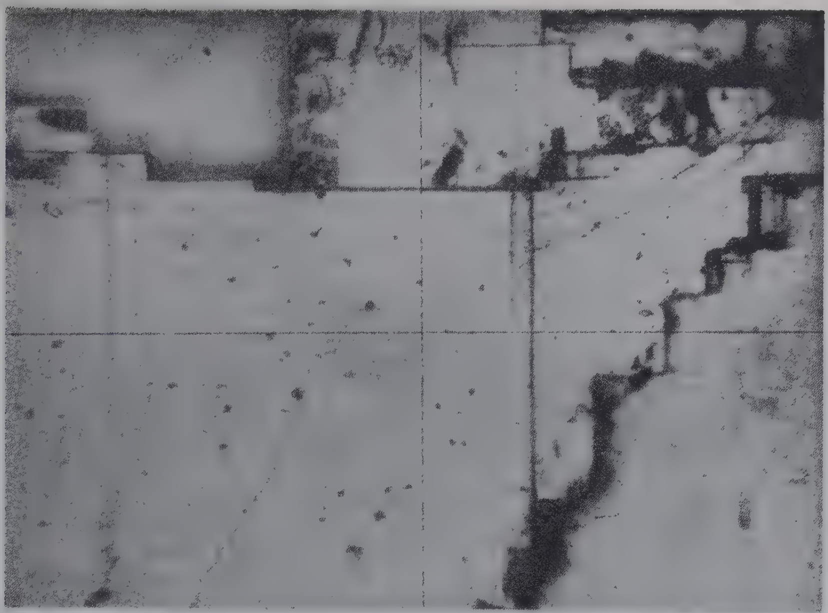


FIGURE 3. Slip lines on a cleavage plane in galena.
Mina Negrilla deposit, Mexico. Photomicrograph, x 26.

In the galena from Mina Negrilla we have found no cleavage fragments on which the slip lines have enabled us to determine the direction of slip. An intersecting system of slip lines on all the cleavage surfaces may be obtained in slip along t [100] and in slip with t [110], if in both these cases it is parallel to all three of the planes T (100), and also by a combination of slip along the two planes T in the direction t [110] with slip along two of the planes T in the direction t [100]. It may be noted that P. Ramdohr (1955), in general, sees in galena only one type of slip under natural conditions -- that with the element T (100) and t [110].

Figure 3 shows that the slip has uniformly encompassed the entire crystal unit of galena. From this circumstance it would appear that at some time there was a completely uniform stress state at all points in the crystal. The situation, however, is probably otherwise. The galena aggregate in the ore from Mina Negrilla is composed of crystal units of different sizes and, in addition, of individual grains of sphalerite scattered throughout; such an aggregate could not have had a completely uniform distribution of stresses. The reason for the uniformity of the slip in the different parts of the unit investigated lies in the mechanism of the process,

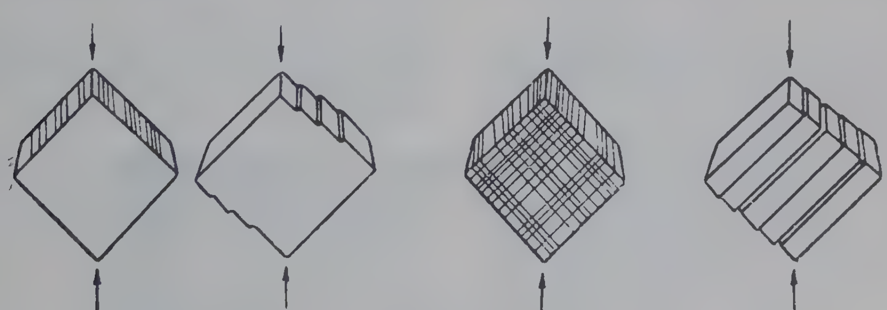


FIGURE 4. Diagram of the formation of slip lines on various faces of a cube of galena

a and b - slip along [100], b - being a diagram of slip in only one plane and one direction, a - being slip in two planes; c and d - slip along [110], d - being a diagram of slip in only one plane and one direction, c - being slip in two planes.

and particularly in the hardening that accompanies slip. During the course of the process, there appear on the slip planes disturbances in the structure which are manifested as "engagements"; these act as a brake on the process and increase the magnitude of the critical tangential stress in slip to such an extent that the deformation must be transferred to a new unit in the structure of the crystal. Thus the phenomenon is repeated many times, gradually encompassing the entire crystal of galena.

Twinning

Mechanical twinning is a displacement of the layers of a crystal by the application of a force that is not accompanied by disruption of the continuity of the crystal and is subordinated to one of the twinning laws. In twinning, the particles of the crystal in being displaced also change their orientation, rotating through 180° around the plane normal to the twinning plane or to the twinning axis.

Whereas slip may take place with a displacement of the layers of a crystal to any distance, the movement of a part of the crystal into a twinning position takes place only after the attainment of a definite unit of displacement of this part of the crystal from its original position. For example, in the case of calcite twinning along (0112), when the optical axis of the crystal has been rotated through an angle of $52^{\circ}30'$, the twinned part must be inclined at an angle greater than $52^{\circ}30'$ divided by 2 = $26^{\circ}15'$; in that case the crystal will spontaneously reach the terminal state, whereas with an inclination less than $26^{\circ}15'$ the crystal will by itself return to its original position.

As in slip, the actual process in twinning differs from its geometrical diagram. According to existing data, twinning does not immediately encompass the entire part of the crystal that moves to a new position, but an embryonic twin begins to appear from one point in the structure of the crystal and a dislocation is created by the movement of atoms into the new position; thereafter the twin gradually spreads throughout the crystal.

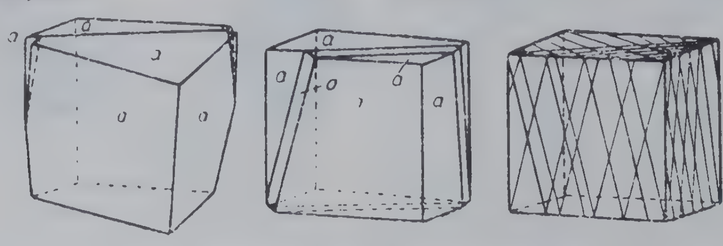
Comparatively small stress is required to effecet such a process, since at each moment the twinning takes place in only a small individual part of the crystal.

According to mineralogical observations, as well as on the basis of experimental data, mechanical twinning is known to take place in a whole number of minerals belonging to different classes and categories.

In contrast to slip, this form of deformation in galena in nature has been discussed in certain papers, which will be cited below when necessary. In the Russian literature on mineralogy, mechanical twinning in galena alone (441) was first noted by P. V. Yeremeyev (1896) in specimens from the old lead mine of Bis-Chek in the region of Semipalatinsk, and was more precisely described and illustrated by Ya. V. Samoylov (1906) in the case of galena from the Nagol'niy Ridge, where the mineral was twinned along (331). In the case of galena, mechanical twinning has been observed with twin planes forming the trigonal trisoctahedra (221), (332), (441), (771) and the tetragonal trisoctahedra (211), (311), (322).

Probably the most common occurrence of twinning is that along (441). A simple growth twin according to this law is illustrated diagramatically in Figure 5a, but in nature mechanical twinning is usually polysynthetic. Figure 5b shows a multiple twin (mechanical twinning?) with only one interpenetrating unit, and Figure 5c shows a polysynthetic twin in which the mechanical twinning is reflected by the lines along two of the surfaces of the form (441) (crystal from Freyberg, cited by Sadebek, 1874.

Our example is represented by the galena from the Darasun deposit in the Transbaikal. Here, too, there is mechanical twinning along (441), as may be easily determined by the magnitude of the angle between the line and the edges of the cube, when the lines are not diagonal to the faces of the cube (fig. 6). These magnitudes for the twinning laws are as follows:



a b c

FIGURE 5. Twinning in galena along (441); Freyberg deposit, Germany

a - simple twin, b - multiple twins, c - polysynthetic twinning.

Twin law	Angle between[4] [01h] and [010]
221	26°34'
332	33°41'
441	14°02'
771	8°08'
211	26°34'
311	18°26.1
322	33°41

FIGURE 6. Polysynthetic mechanical twins in galena along (441). Darasun deposit, Transbaykal. Photomicrograph magnified X 12.

The photograph (see fig. 6) of one of the surfaces of cubic cleavage shows twins along two faces of the trigonal trisoctahedron (441); one of these produces incipient twins along the plane diagonal to the cube, and the others, which are diagnostic, at an angle to the edge of the cube (by measurements under the microscope, 77° or 13°), which also occurs in twinning along (441).

Polygonization

Along with the two types of deformation considered above, slip and twinning, the attention of experimenters has been concentrated recently on another type of very widespread plastic deformation.[5] But the nature of this type of deformation has still not been sufficiently investigated. There is little doubt that this includes different forms of deformation which will in future be more clearly distinguished and characterized.

The common feature in the deformation of this type lies in the fact that this deformation in the crystal results in blocks which are rotated relative both to the original crystal and to each other. Thus the crystal is deformed, but its continuity is maintained. Within each of these blocks the crystal lattice remains undistorted. The boundary between the blocks are in general not crystallographic boundaries, and thus cannot be expressed directly by the crystallographic indices. The maintenance of the body's continuity indicates that the crystal

[4] It will be seen that by these angles the twins along (332) and (322), and also along (221) and (211), cannot be distinguished from each other.

[5] In the case of this type of deformation, certain additional literature in physics must be cited which is still not reflected in texts or surveys: A.B. Zemtsov, M.V. Klassen-Neklyudova and A.A. Urusovskaya (1953); M.V. Klassen-Neklyudova and A.A. Urusovskaya (1956a and 1956b); and Ye. V. Kolontsova, N.V. Telegina and G.N. Plavnik (1956).

lattices of the individual blocks are discontinuously connected (on the nature of this connection see below). The blocks differ greatly in size: from macroscopic, measurable in millimeters and even in centimeters, to sub-microscopic, which may be discerned only by means of X-ray analysis.

The shapes of the blocks also vary. Wedges, plates and isometric volumes, as well as intermediate forms, exist.

Because of this peculiarity such deformations have been given a number of different terms in the literature: twinning along irrational planes, formation of zones of deformation, zones of accommodation, lamination, polygonization, formation of glide bands, etc.

To arrive at some sort of type name for the several different kinds of dislocations considered here, we shall use the term "blocking" to designate the formation of blocks of different shapes and sizes similar to the blocks which appear in certain cases in the growth of crystals (producing the block-like or mosiac structure of the latter). The mechanism of deformation, at least the type of block formation that is known under the name polygonization, may be explained as follows: In "blocking" the plastic flow begins with the development of dislocations of the so-called "wedge" type, as already mentioned above in the discussion of the mechanism of slip. The wedge dislocation may be represented as in the diagram in Figure 7.

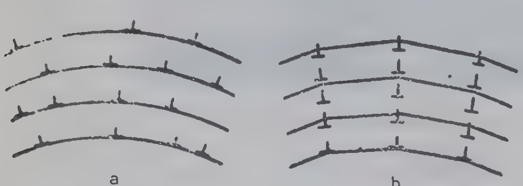


FIGURE 7. Diagram of the formation and displacement of wedge dislocations in bending

a - bending with random distribution of dislocations
b - dislocations displaced and distributed by rows, dividing the crystal into blocks each with a normal lattice.

The deformations we are concerned with here are accompanied by the appearance of a multitude of dislocations, the various distributions of which within the crystal may produce the most diverse kinds of deformation, apart from the curvature shown in the illustration. As these dislocations arise they are distributed at random throughout the body of the crystal (fig. 7a). The crystal is deformed in this manner, but the formation of blocks still does not take place.

The result of the deformation under consideration here, the creation of blocks, is obtained after redistribution of the dislocation. With the course of time, and under favorable conditions, the dislocations are capable of being displaced along rows and in layers of the structure, forming stable groups along definite lines and in definite planes of a structure, as shown diagrammatically in Figure 7b. Since in this process the parts of the structure in the interstices between the group of dislocations are freed from distortion, individual blocks of undisturbed structure are produced; these are rotated relative to each other through a certain angle whose magnitude depends on the degree of deformation of the body. The size of the blocks and the magnitude of the rotation between them may vary; the angles are normally expressed by several degrees. Theoretical attempts, however, have been made to explain rotations as great as 30°, although from the standpoint of energy the problem has been solved only for small angles between the crystal lattices.

The blocks are not connected to each other, so-to-speak, by a simple attachment; the continuity of the crystal structure is preserved by means of dislocations between the different blocks.

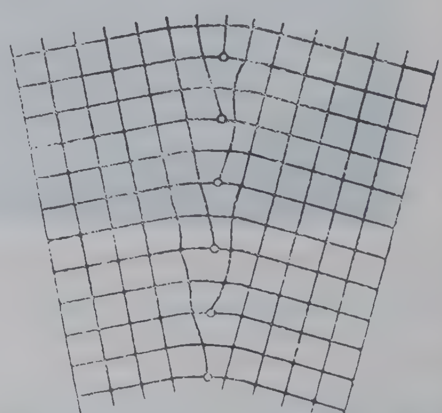


FIGURE 8. Diagram of the connection between the crystal lattices of adjacent blocks in the dislocation zone.

The nature of the boundaries between the blocks in diagrammed in Figure 8, which shows regularly constructed parts of the structure connected by distorted layers whose dislocations are arranged linearly.

When the blocks are rotated cross-wise the picture becomes more complicated. This writer knows of no attempt to consider the formation of blocks of minerals on the basis of a dislocational mechanism of deformation. Nevertheless this phenomenon is very widely developed in nature. It may be that "blocking" will turn out to be the basic type of deformation in

the overwhelming majority of minerals, but this can be determined only after making an enormous number of observations.

"Blocking" with the formation of displaced "wedges", which may accompany mechanical twinning, is shown by the diagram in Figure 9, which represents a deformed or bent crystal whose two parts have been displaced to the distance S by the development of a system of glide planes between wedge-shaped parts. The dislocated part as a whole is called a glide band.

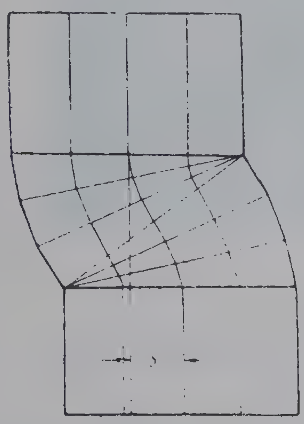


FIGURE 9. Diagram of a crystal with a glide band composed of wedge-shaped blocks; the longitudinal bands are slip lines.

Within the glide band the wedge-shaped blocks are rotated in various directions in different parts, but mainly around the direction perpendicular to the plane of the illustration, each block being rotated through several degrees; in addition, there may also be a secondary rotation around some oblique direction.

Such block formation, which was observed in physics only in recent years, was established in the case of minerals by O. Muegge as early as 1898. This phenomenon is manifested most clearly in kyanite.

Another form of blocking, known in Soviet literature as "polygonization", is extremely typical, especially in the case of galena. This results in the formation of blocks of various polygonal shapes, rotated relative to each other through various angles which are primarily of small magnitude -- several degrees in all. These rotations take place in varying directions, although among them a tendency toward a certain regularity has often appeared.

Figure 10 shows a photograph of a specimen of deformed galena from the Berezov gold-ore deposit in the Urals, and Figure 11 shows its structure, the directions and the angles of

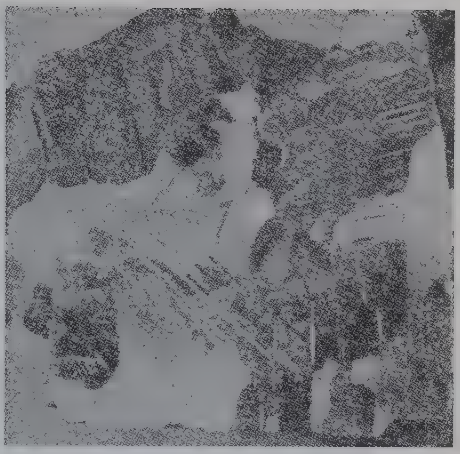


FIGURE 10. Deformation in galena from the Berezov gold-ore deposit in the Urals. Magnification X 7.

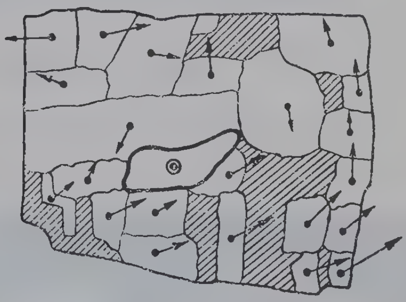


FIGURE 11. Diagram showing the structure of the specimen illustrated by the photograph in Figure 10.

The angle p of the block encircled by the heavy line is regarded as zero. The directions of the rotations of the other blocks are shown by the vectors and the magnitudes of the rotations by the length of the vectors, each degree being two mm.

rotation of the block, as obtained by measurement with a goniometer. These measurements were made by V. Lazarenko [not in references]. The goniometric measurements could not be made by direct light, but only by reflection; they are accurate to about 1°. As may be observed, in the general picture of disorientation of the block in the lower right part of the specimen, there is a more or less regular curvature. The angles between adjacent blocks are approximately $2\text{-}3^{\circ}$, but in some cases (the two blocks in the upper left corner inclined in opposite directions) the angle is as great as 8°. Between the measured blocks there are parts cross-hatched (in fig. 11) which could not be measured because of the uncipherable reflections. These parts of the crystal are more intensively deformed, and have been divided into blocks of smaller orders.

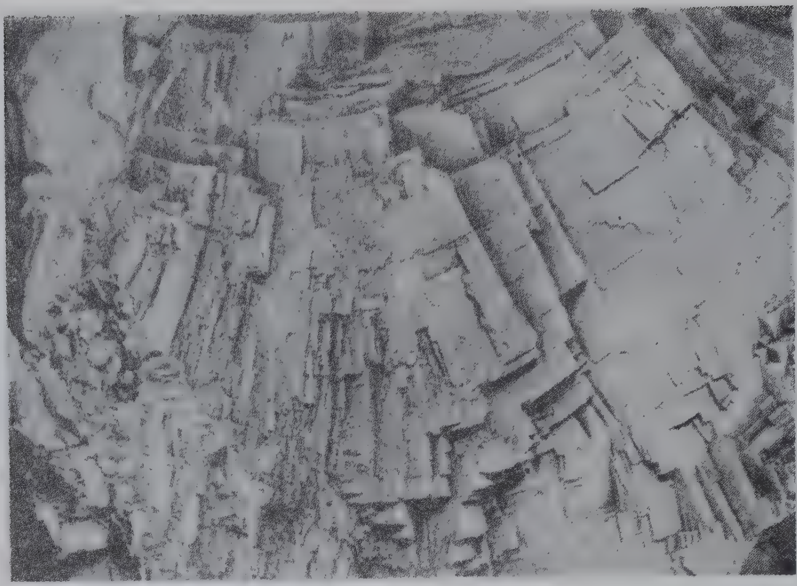


FIGURE 12. Curvature in galena produced by block-by-block displacement. Berezov gold-ore deposit, Urals. Magnification X 3.

For the photograph, the specimen was "retouched" over hot magnesium smoke.

Figure 13. Convex curvatures in galena resulting from block-by-block displacement. Berezov gold-ore deposit, Urals. Magnification X 2.

Specimen has been smoked.

Other specimens of galena show the most varied deformations obtained as a result of some development and redistribution of the blocks, macroscopically (measurements of these large specimens could not be made on the available goniometers) producing curvatures (fig. 12), convexities (fig. 13) and other forms of deformation. In the course of such deformation the degree of disorientation of the block gradually increases, and the dimensions of the latter decrease as a result of the formation of blocks of secondary orders.

The resulting general picture is one of the transformation of monocrystals into granular aggregates. This phenomenon generally corresponds to the process of granulitization, but its analysis remains the task of future investigation. The question arises of the nature of this granulitization in other materials, which at least in some cases may also follow a similar mechanism.

The granular aggregates of galena were studied by D. Schakhner-Korn, who determined the orientation of the grains by the angles between the cleavage traces in thin sections (Korn, N. D.; Schachner-Korn, 1948, 1954; Schneiderhoehn and Ramdohr, 1934), considering some of the granular structures as resulting from deposition and others from recrystallization. But in this study the process itself is not discovered and the results require new analysis.

It should be noted that in both the forms of

block deformation described here the mineral aggregates break not along the boundaries of the blocks, but along the cleavage (unless the boundaries between the blocks are marked by brittle deformations of cleavage or rupture).

Above we have considered macroscopic and microscopic blocks, but in nature (as in the laboratory and in engineering) blocking also takes place on a sub-microscopic scale. This can be discovered, as already mentioned, only by X-ray analysis. This form of block formation is especially characteristic of micas, and also of chlorites, talc, pyrophyllite, molybdenite and other minerals with a micaceous structure.

CONCLUDING REMARKS

The simple manifestations of plastic flow in galena considered above -- slip, twinning and block formation -- characterize most cases of change in the shape of the mineral under the action of mechanical forces. Blocking deserves special attention as a type of deformation that is particularly distinguishable in mineralogy and very widespread in nature.

What are the relationships between these different forms of deformation in galena? In regard to this question we may cite the following observations, derived from the large amount of material in the famous Berezov deposit in Urals. Slip undoubtedly results from the very smallest scale of deformation in galena, when the cleavage plane in the mineral still retains its mirror smoothness. Galena with mechanical twinning is encountered in the more deformed specimens, where the cleavage planes are somewhat distorted; slip lines together with twinning could not be observed. Finally, block formation corresponds to visible distortions in the form of the galena; the blocks, however, show neither slip lines nor mechanical twinning.

This individualization of the different types of plastic deformation in galena may indicate either that they have developed successively, in the order indicated, so that each deformation eliminates the traces of the preceeding one, or else that each type of deformation arises at once under conditions of mechanical action of the galena which are specific for it alone.

As a result of the various deformations under different conditions in nature, the crystals and aggregates of galena have acquired an endless variety of distorted forms and internal structures; the simple deformations are the "alphabet" of their analysis. These peculiarities of the mineral indicate various stresses in nature -- bending, torsional, compressive, tensional and every possible combination of these.[6] The result of these deformations, of course, also fixes the magnitude and the direction of the corresponding forces.

[6] See the description of the scars on the quartzes from the Berezov deposit by the deformed galena and tetrahedrite ores (Grigor'yev, 1957).

In the case of all the forms and examples of deformations considered above, a crystallomorphological characterization was given. It would naturally be desirable also to have accurate, quantitative data on the stresses which cause the various deformations, so as to draw conclusions on the magnitudes of the forces that act in nature on the minerals.

Experiments on minerals or synthetic analogues of minerals have already produced certain quantitative data on the stresses involved in deformations -- the values of the critical tangential and normal stresses. Such experiments show that the quantitative data to a considerable degree depend on many factors. In addition to chemical admixtures, the "structurally felt" mechanical properties of the minerals are also strongly influenced by the peculiar features of the structure of actual crystals and particularly by disruptions and dislocations of the crystal lattice, not to mention the effect of preceding deformations.

In general it appears that in the case of minerals it is not possible to cite any mechanical constants, since one cannot take any specimen of minerals as standard, and the average values of the constants will be unsatisfactory because their plus-or-minus tolerances may be several times greater than the magnitude of the "constants" themselves.

Consequently at the present time, when many of the conditions of natural deformations remain unknown, it is difficult to calculate the absolute quantitative values of the stresses and forces involved in the deformation of minerals, including galena. But the actual picture of the elementary manifestations of plastic deformation in galena, as considered in the example in this article, are of very general interest. Plastic deformations in all other minerals belong to the same category of phenomena.

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[See also: Schachner-Korn]

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GEOBOTANICAL INDICATORS OF BITUMEN[1]

By

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• translated by Gaida M. Hughes[2] •

ABSTRACT

Abnormal plant growth and early or second flowering are related to the bitumen content of the soil. While such abnormalities have previously been noted, geobotanists of the 1950 All-Union Aerogeologic Trust expedition carried the study to a more definitive level. By comparing vegetation of known bitumen-bearing sections against "control" sections, they related specific abnormalities of plants to the presence of bitumens. The studies were carried out in arid regions of Western Kazakhstan and the northern Caspian Sea coast. Plants were classed according to whether the abnormalities were 1) of unusual size without alteration of the original form, for which 28 species are listed; 2) notably increased branching, 8 species; and 3) second blooming, 12 species. Other abnormalities and distortions are described. Subsequent investigations testing the preliminary data shows that plants are reliable indicators of oil bitumens in the soil. --A. Eustus.

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At the present time a great number of geochemical methods are used in prospecting for oil. They are based on the assumption that substances from the oil deposits migrate upward to the surface layers of the earth's crust. Several methods are known which enable one to detect the presence of by-products from oil deposits by changes which these substances produce in the surrounding medium.

Among these methods of considerable interest are two biological methods: bacteriological and geobotanical.

The bacteriological method is based on the ability of some micro-organisms to assimilate selectively certain gases (methane, propane, ethane and others). Certain groups of bacteria serve as indicators of oil deposits in an area (Mogilevsky, 1940).

The geobotanical method is based on the utilization of those specific changes which plants undergo in the presence of oil bitumen, as indicators of the bitumen content of soils.

At present there are no separate works devoted entirely to the study of the influence which oil bitumen has on plants. In literature, however, one may find some direct and indirect statements by investigators in this area, which provide some idea about the behavior of plants in the presence of bitumen. Thus, it is known that yields from agricultural crops have been increased by mulching the soil with oil bitumen (Banasevich, 1941a), and by using waste products from oil refineries as fertilizer (Guseynov, 1949 [1951?]).

A stimulated growth of plants was also observed in experiments where sand was fortified with bituminous emulsion (Banasevich, 1941b, Gayel et al., 1935 [1938?]).

An explanation of these phenomena is sought by Guseynov, Banasevich and others in the definite physical-chemical changes which occur in the environment under the influence of bitumen. They found that in experiments using waste "gumbrin" and bitumen emulsion, the structure of the soil is improved, the moisture capacity and temperature of the soil increases, in addition, the quantity of assimilable phosphoric acid doubles, and the pH of the soil is lowered. It is also known that the intensity of nitrofication is related to the quantity of bitumen present in the soil (Remezov, 1938).

A number of observations indicate that soils with a high bitumen content produce certain definite plant forms which are adapted to this type of soil.

Of great interest in this respect are the observations of K. F. Shchapova (1938), who in the northeastern part of Caspian Sea (the area directly adjacent to the Embensk salt dome oil territory) found giant Zostera nana up to 1 m in height, which is approximately five times taller than the usual height for this species.

P. D. Yaroshenko [not in references], while studying the vegetation on volcanic mud in southeastern Shirvan found a new form of Salsola

[1] Translated from Geobotanicheskiye pikazateli bituminoznosti: in symposium volume Geobotanicheskiye metody pri geologicheskikh issledovaniyakh [Geobotanical methods for Geologic Investigations]: Trudy, Vsesoyuznogo Aerogeologicheskogo Tresta, Ministerstva geologii i okhrany nedr, no. 1, pp 99-117, Gosgeoltekhizdat, 1955. Reviewed for technical content by Herbert E. Hawkes, Jr.

[2] U.S. Geological Survey.

ericoides which he named Salsola ericoides variety folioloides. It differed from the ordinary form by its branching and the color of leaves, bark, and wood pulp.

M. G. Popov (1949, p. 492) names a whole series of endemic plants found near the Magunlan volcano on Sakhalin. One of the endemic species found by him — Artemisia limosa H. Koidz was different from the closely related Artemisia borealis Pall. species in that it had a two-year development cycle and some minor morphological differences: small amount of foliage, simply cleaved leaves with narrow lobes and short stems. In Popov's opinion the endemic vegetation on the Magunlan volcanic mud "developed as a result of edaphic soil influences which the volcanic mud has on plants growing on it". It is entirely possible that these special edaphic soil influences are those specific properties of the mud which appear when the mud has a high bitumen content.

From this summary of literature it may be seen that investigations hitherto have been directed toward studying the effect of oil bitumen on plants mostly for the purpose of utilizing it as a cementing agent for strengthening loose sands.

The possibility of utilizing plants as bitumen indicators in prospecting for oil was for the first time suggested in 1949 by S. V. Viktorov and Ye. A. Vostokova [not in references].

Following a detailed study of plants growing in kir [adobe?] fields and areas with shallow oil deposits, the above authors found that in the presence of oil bitumen, plants acquire very characteristic and easily noticeable changes in their external appearance. The great majority of plants growing on bituminous areas were distinguished by their giant size and frequently displayed abnormal deviations which greatly altered their external appearance. Thus, giant Suaeda physophora Pall. (80 to 90 cm tall; 60 cm in diameter) with deformed shoots which formed a unique curve, was found in one oil field near the oil wells where the ground was saturated with oil spilled in pumping. Stalks of Suaeda physophora Pall. in this area were of a bright purple color (this is generally characteristic of this specie after it has bloomed, but usually appears much later).

In the plant belt surrounding the kir fields we observed a second blooming and second vegetation period during the latter part of October and early November. The same phenomenon was also observed for plants growing in the cracks between "kir" plates [adobe blocks]. A total of 34 species from 10 families were studied, and it was found that the above-named changes were exhibited by plants representing the most varied systematic groups. Evidently, here we did not come in contact with a narrow range of adaptability, characteristic only for a small number of species, but rather with some kind of a broad, general biologic law.

In 1950-1951 the geobotanists of the All-Union Aerogeologic Trust for the first time attempted to utilize the established changes in plants caused by bitumen as indicators in prospecting for oil.

In 1950 a special geobotanical preliminary survey (S. V. Viktorov, Ye. A. Vostokova, A. D. Grigoryeva, M. S. Kasyanova) [not in references] made it possible to separate a number of areas with a high bitumen content and to recommend these areas to geologists who were studying the northeastern shore of the Caspian Sea. Results obtained in this investigation were later verified by more detailed surveys.

During the past several years the geobotanical association of the All-Union Aerogeologic Trust conducted further studies in this direction covering considerable areas of Eastern and Western Kazakhstan and Turkmenia (Uzboy and Emba regions, and areas between the Volga and the Urals). This work according to its character is divided into two stages.

The first stage consisted of a comparative study of plants in two sections — a standard section (where the presence of oil bitumen in the soil was already known) and a control section where bitumen was not present. A study of these sections permitted us to learn the geobotanical characteristics of the presence of bitumen.

The second stage consisted of searching for bitumen-bearing areas using data gathered from geobotanical observations. A discussion of each of these stages will follow.

Investigations began with the selection of areas of 250 to 500 m each where the presence of oil bitumen in the soil had already been established by special analyses. Samples for analysis were taken from those layers of soil which were accessible to roots, as well as from underlying rock. Analyses were conducted by the luminescent method, but those for control purposes by the Soxhlet extraction apparatus.

Control sections were selected where the ecologic conditions were similar to those of the standard sections. Special care was exercised in order that the following very important factors be kept identical: the position of studied section in relief, the closely related hydrogeologic conditions and salinity of the soil, the lithologic composition of the substratum, the thickness of alluvial deposits, as well as the type of plant covering be kept identical.

In addition to the detailed description of the plant association, in each section a detailed

study was also made of all species which composed this association, and a mass measuring of the heighth and "diameter" of plants was conducted. From 25 to 100 measurements per specie were taken in each section. "Diameter" was the distance between the ends of two most distant, opposite branches.

A considerable number of sections were separated and studied by the geobotanical association of All-Union Aerogeobotanic Trust. Below we present the data on some standard bitumen containing sections.

WESTERN KAZAKHSTAN

Section 1 was located at the edge of a Solonchak. There, along the very edge of the shore, on a wet solonchak, grew numerous extremely deformed Salicornia herbacea L. individuals with shortened seqments, club-shaped tips of shoots, and distorted stems. Profuse branching of Salicornia herbacea L. here forms low-grown, luxuriant, spherical-shaped "bushes" 15 to 25 cm high.

Holocnemum strobilaceum M.B., plants, which form a band along the shore of the sor are greatly retarded. Numerous dead shoots are characterized by whiteness on the tips.

Obione verrucifera Mog., situated in the appearance of a belt toward the periphery from Holocnemum strobilaceum M. B., shows no deviation from its usual form. In the next band toward the periphery, situated in a depression between the sand massif we observed individuals of Statice [Limonium] gmelini Willd., which were approximately 150 cm tall (ordinary height of this specie does not exceed 70 to 75 cm).

Section 2 is located adjacent to a chain of ascending, highly mineralized springs and natural vents of fuel gas which, evidently, have some relation to the tectonic disturbances in the salt-dome area.

Salicornia herbacea L., which grows directly at the outlets of gas is very dwarfed, low-growing poorly branched, it has deformed, twisted shoots and short, bloated segments. At a distance of 50 m from the chain of vents, Salicornia herbacea L. is luxuriant, has a spherical shape because of abundant branching, and also twisted shoots and club-shaped segments; it is up to 40 cm tall with a diameter of 59 cm.

The shore of the area is occupied by Atriplex cana, Statice [Limonium] suffruticosa and Artemisia incana. Atriplex cana and Statice suffraticosa here are of tremendous size, the first being up to 90 cm tall with a 150 cm diameter (its ordinary height in the flora of the Central European part of the U. S. S. R., according to Mayevsky, is 20-50 cm); Statice suffruticosa here is 58 cm tall with a 96 cm diameter (ordinary height is 15 to 25 cm). Artemisia cana has ordinary appearance and measurements.

Section 3 is located on the shore of the Solonchak. Salicornia herbacea L., similar to that described above, forms a belt which comes into contrast with ascending vents. Directly adjacent to the vents, the height of Salicornia herbacea L. is up to 77 cm tall.

Huge Salsola foliosa L. Schrad individuals are scattered along the shore of the solonchak, and their maximum height attained is 95 cm with a 130 cm diameter (their average height under ordinary conditions does not exceed 25 to 50 cm).

Enormous size was also characteristic for other plants composing this association: Suaeda physophora, 105 cm tall with a 103 cm diameter; Artemisia pauciflora Web., — 80 cm tall; low grown Anabasis aphylla bushes with wide, laterally spread, horizontally directed branches is up to 80 cm tall and have a 130 cm diameter; and Anabasis aphylla a cushion-like appearance.

Section 4 was a shallow gulch on the shore of the Solonchak and had a swollen solonchak on the bottom. The following unusual plant forms were encountered: Anabasis aphylla L., up to 90 cm tall with a diameter of 170 cm; Frankenia hirsuta L., — very large individuals with thick, interlaced branches grew up to 70 cm in height (under ordinary conditions — 10 to 35 cm tall); Ofaiston monandrum (Pall.) Mog. is up to 34 cm tall (under ordinary conditions 10 to 20 cm); unusually large Petrosimonia triandra (Pall.) Simonsk. plants were of extremely branched spherical form, up to 50 cm tall with a diameter of 80 cm (figure 1); Silicornia herbacea L. was deformed, up to 40 cm tall; Suaeda physophora was up to 108 cm tall with a diameter of 180 cm. Hypertrophy was also noted in the following species: Artemisia arenaria D. C., Eurotia ceratoides C. A. M., Tanacetum vulgare L.

Section 5 was the shore of the solonchak. In the Anabasis aphylla L.-Artemisia incana association growing here, Anabasis aphylla was up to 85 cm tall with a diameter of 150 cm; but Artemisia incana had a more ordinary appearance and measurements.

Atriplex cana in Atriplex cana-Artemisia incana associations shows a noticeable lack of proportion and has a candle-like shape (height 150 cm; diameter 65 cm).

Salsola branchiata Pall., which is also found in this association, because of abundant branching, has a spherical shape (height to 32 cm; diameter 42 cm), height on control sections 15 cm,branching is insignificant.

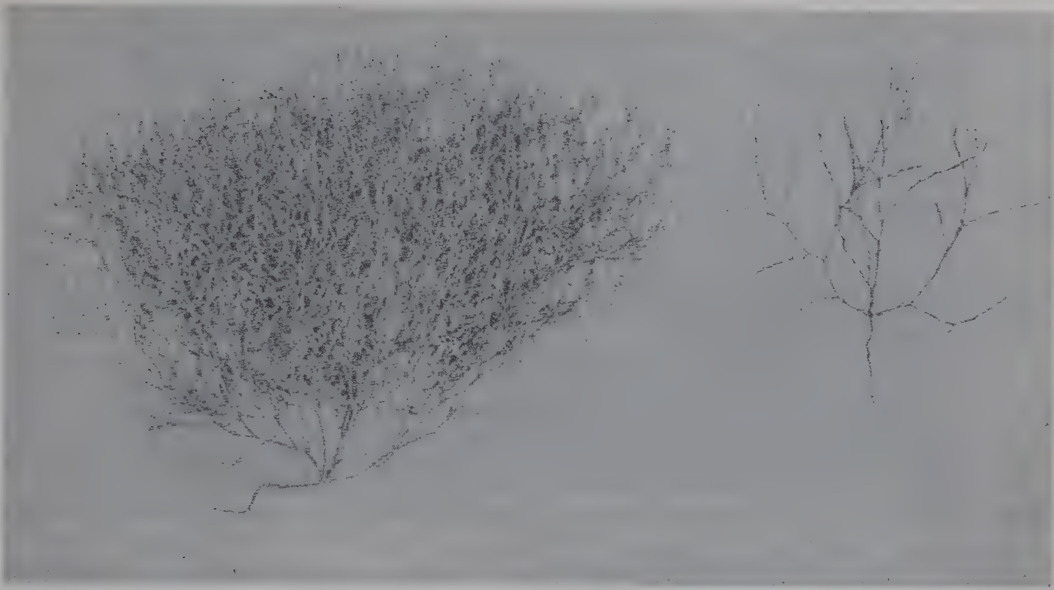

FIGURE 1. Petrosimonia triandra on soil containing bitumen (left) and on bitumen-free soil (right)

Two forms of Echinepsilon sedeides (Pall.) Mog. were represented here: a candle-shaped one which was up to 80 cm tall, and a spherical form with an unusual amount of branching, and up to 40-45 cm in height and a 50-55 cm diameter.

NORTHEASTERN CASPIAN SEA COAST

Section 6 is located on islands in the Metrvy Kultah solonchak lake. There were observed hypertrophic Zygophyllum ramosissium with hanging, luxuriant crowns and Salsola branchiata.

Section 7 is a sandy ridge. Giant-sized Alhagi pseudalhagi (M. B.) Desv. and Artemisia maritima grow here, and it was observed that Atraphaxis spinosa L. bloomed here for a second time.

Section 8 is located in a solonchak natural boundary in the basin of the Emba river lowlands. Many giant Kalidium caspicum and Statice [Limonium] Gmelini plants were observed here, and a second vegetation was noted for Atropsis distans (L.) Grisev., Agropyrum [Agropyron?] ramosum Richt., and Frankenia hirsuta.

Section 9 was located on a solonetz plain. The plant cover here was composed of an association of Anabasis depressa, notable at first glance for its abnormal appearance. Anabasis depressa was very dwarfed and had very many dead segments. Along with the Anabasis depressa here grow extremely well-developed Atriplex cana C. A. M. plants which are 80 cm tall and 60 to 80 cm in diameter.

Section 10 is a swollen solonchak with a saltwort cover. The following giant plants grow in this area: Salsola soda L., Petrosimonia glaucescons, Petrosimonia appositifolia Litw., Halimocnemis Karelini, Mog-Tand., Halimocnemis sclerosperm C. A. M., Salsola crassa M. B. (figure 2), Atriplex tatarica L. and Salsola soda, which here grows 25 to 30 cm tall and is normally 50 to 80 cm in diameter. Atriplex tatarica is up to 1.6 m tall and 1.5 m in diameter.

The above plants grow in a narrow band stretching from northwest to southeast from the fracture line along the wing of salt dome.

Section 11 is a narrow solonchak with a band of a luxuriously developed halophitic plants. Especially well developed is Salicornia herbacea, Statice suffruticosa. Ofaiston monandrum is also unusually large and well branched, up to 45 m in height and 80 cm in diameter.

The above descriptions of sections may be supplemented by data obtained from other regions.

S. V. Viktorov and L. F. Voronkova in 1953, while working on bitumen substrata in Kara-Kum and Ustyurt, observed some very characteristic forms of several widely prevalent species. The found a "bitumen" form of Ammodendron connollyi which grew in giant, broom-shaped bushes which almost did not branch at all and did not have a main stem.

Nanophyton erinaceum, normally cushion-shaped in bitumen-bearing soils, also has a form which grows upward (the so-called "erect" form). This form retains its characteristics

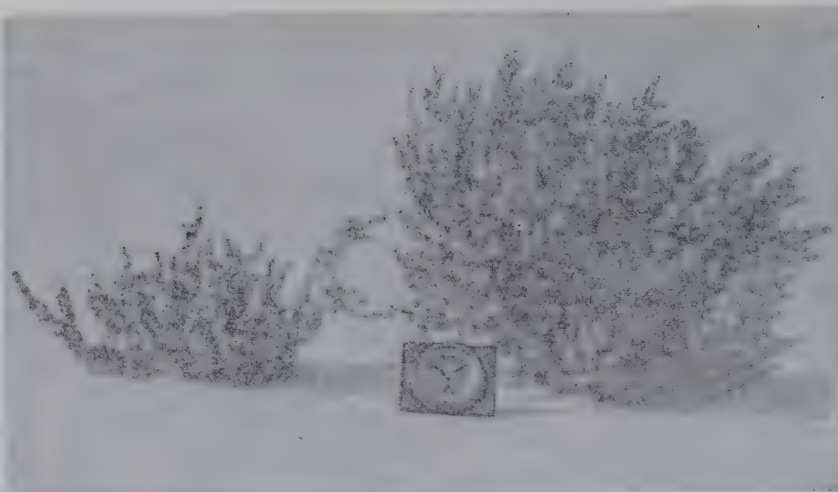

FIGURE 2. Salsola crassa on a bitumen-bearing section (right) and on a bitumen-free section (on the left)

during all stages of the individual's development.

Halocnemun strobilaceum and Kalidium foliatum in some bitumen-bearing areas in summer had an unusual orange-violet color.

The above-discussed factual data indicate that plants which have developed on bitumen-bearing soils show a significant variety of morphological and pathological changes.

1. By far the greatest number of species studied, in the presence of bitumen acquire giant proportions. Giant size is manifested by all parts of the plant. There are instances where some species retain proportions for some of their parts, and the general appearance of the plants, except for their size, remains the same. The following species belong to this class:

Alhagi pseudalhagi (M. B.) Desv.
Atriplex cana C. A. M.
A. tatarica L.
A. dimophostegia Kar. et Kir.
Anabasis aphylla L.
Artemisia incana Kell.
A. arenaria Web.
A. pauciflora Web.
Agrophyrum sibiricum (Willd.) P. B.
Echinopsilon sedoides (Pall.) Mog.
Eurotia ceratoides C. A. M.
Eragrostis pilosa P. B.
Frankenia hirsuta L.
F. pulverulenta L.
Halimocnemis sclerosperma (Pall.) C. A. M.
H. Karelini Mog.
Kalidium caspicum Ung.
Kochia prostrata Schrad.
Melilotus ruthenicus M. B.
Ofaiston monandrum (Pall.) Mog.
Petrosimonia crassifolia (Pall.) Bge.
P. glaucescens Ilyin
Salsola mutica C. A. M.
S. rigida Pall.
Statice Gmelini Willd.
Suaeda physophora Pall.
S. prostrata Pall.
S. confusa Ilyin
Zygophyllum ramosissimum

For example, the ratio of the size of Anabasis aphylla grown on bitumen-bearing substrata, and Anabasis aphylla grown under control conditions is shown on the diagram of Figure 4.

2. The specific forms which plants acquire over bitumen-bearing substrata in their entire appearance greatly differ from the appearance that a given widely distributed specie has when it grows under ordinary conditions.

The following changes may be distinguished in the external appearance of plants growing on bitumen-containing substrata.

Plants which normally have a cushion-shape appearance, acquire a candlelike, upright form due to an increased rate of growth of the main stalk and a slower rate of growth of lateral stems. Such forms are observed in Echinopsilon sedoides (Pall.) Mog., Atriplex cana C. A. M. (figure 3), and Nanophiton erinaceum.

Spherical appearance, which results from an increased branching of lateral stems and shoots, is characteristic for the following species:

Frankenia pulverulenta L.
Halimocnemis sclerosperma
H. Karelini.
Petrosimonia glaucescens Ilyin
P. oppositifolia Litw.

Salicornia herbacea L.
Salsola mutica C. A. M.
S. soda L.

Flattened form which results from a retarded rate of growth of the main stem and an increased growth of lateral shoots. This form is frequently observed in Anabasis aphylla L., Atriplex cana C. A. M. (figure 3), and other species.

Broom-like appearance, as described for Ammodendron Connollyi Bge., results when the main stalk does not develop at all.

It has been observed more than once that one specie may acquire different forms. An excellent illustration of this is Atriplex cana C. A. M., which in some bitumen-bearing sections had a characteristic form (up to 150 cm tall, not more than 50 cm in diameter), but in other sections had a flattened form (up to 150 cm in diameter, but not more than 90 cm in height).

3. Acquisition of deformed organs (crooked stems, thickened and shortened shoots, club-shaped, swollen segments, etc.) was observed only in a few species of Salicornia herbacea L., Suaeda confusa Ilyin, Kalidium foliatum Mog.

4. Oppressed appearance in the presence of oil bitumen, which resulted from retarded growth and development, was noted only for Holocnemum strobilaceum M. B., which in all instances was very oppressed. Often, but not always, Anabasis depressa growing on bitumen-bearing substrata had an oppressed appearance. Oppressed appearance, evidently, may not serve as a reliable indication of bituminous substrata, inasmuch as oppressed appearance of the species mentioned frequently may be caused by such factors as insufficient moisture and heavy predominance of sulfates over chlorides in the salt complex.

5. Change in the development cycle with a tendency toward a two-cycle development.

Second blooming and vegetation in late fall was noted for the following species which grow on bitumen-bearing sections:

Astragalus brachilobus
Atrafaxis spinosa
Atropis distans
Carex stenophylla
Dianthus leptopetalus
Eragrostis pilosa
Potentilla opaciformis
Pyrethrum achillaeifolium
Salvia nemorosa
Silene wolgensis
Statice caspica
Stipa capillata

Second blooming was not observed for all species which grew in bituminous sections, nor for all individuals of the same species, nor in all sections studied. Therefore, second blooming may not serve as a reliable indicator in prospecting for oil.

By botanical indicators a number of sections were selected as promising for bitumen. Investigation confirmed the presence of oil bitumen in the soil. Most of the selected sections turned out to be associated with salt-dome structures.

In a well-developed salt-dome structure region, we compared the distribution of bitumen containing sections selected on basis of geobotanical indications with a geological map of salt-dome structures. As a result of this comparison we found that most of the sections were associated with faults in them. This serves as an evidence that bitumen migrates from oil deposits upward along these faults into the weathered surface layers of soil. Consequently, the sections with specific forms of plants in the area of the salt dome may be used as indicators of the relationship that exists between a given salt dome and oil deposits. By the location of these sections it is sometimes possible also to determine the location of line of tectonic disturbance in the salt-dome area.

Difficulties in the methodology of work may arise when botanical criteria are applied in prospecting for oil. This is especially true for inexperienced investigators. First of all, in order to find bitumen-bearing sections by botanical signs, it is necessary to choose the proper time of the year for study of plants. The point is, that such a sign as, for example, the giant size in different plants may appear and become noticeable at different times.

Annual plants which end their development cycle in early summer make it possible even in spring to judge the bitumen content of substrata on which they grow. Annual plants which bear fruit considerably later, such as Salsola foliosa, for example, and perennials which have only their underground parts living during the winter (the part above the ground reappears anew every spring), on bitumen-containing soils during the first part of summer may have a very normal size and appearance; hypertrophy at this time will not yet be sufficiently apparent and therefore may go unnoticed. In our work there were instances when, during a survey conducted in the autumn, we found a number of bitumen-bearing sections by the unique characteristics of the plant cover in an area, which, during a preliminary prospecting conducted in early summer, was considered as not containing bitumen.

The most convenient indicators in this respect are bushes (such as the above-described Atriplex cana, Anabasis aphylla L., and Suaeda physophora).

When bitumen containing sections are selected by the giant size of plants growing there, it is important that an extremely careful analysis be made of the ecologic conditions of the habitat.

In arid regions some plants may be larger than the general background of plants due to more moisture from fresh water lenses, etc. Soil salinity is important for solonchak and solonetz plants. Salicornia herbacea in Keller's experiments, when grown on a nonsaline soil, developed very well and reached considerable size.

Special care should be exercised in using oppressed appearance of some plants as indicators of bitumen. Oppressed appearance, as it has already been mentioned, may result from a whole series of other causes: insufficient moisture, excess salinity, etc.

Second blooming, as one of the indicators of bitumen content of substrata, is more reliable for species which bloom early and ordinarily have a one-cycle development. Entire families are known to have a general tendency toward second blooming. This fact should always be borne in mind when an attempt is made to select bitumen containing sections by using the second blooming of plants as an indicator.

Utilization of all the above-mentioned biological indicators in prospecting is more convenient and provides more reliable results.

All plants in the same bitumen containing section will not always have the same type of characteristic traits. First, a reaction with bitumen at present is known to occur only in a few plants; evidently, there are species which are indifferent to the presence of oil bitumen. Secondly, it should be remembered that the roots of different species, and of different individuals of the same species reach different levels of the soil, and thus may be located in areas which have a different bitumen content. Therefore, in studying the reaction of one given species to bitumen, a hasty conclusion about its indifference to bitumen should not be made only on the grounds that a section which contains hypertrophical forms of other species this one species has a normal appearance. It is therefore necessary to test the soil and rocks for bitumen (especially in control sections); and samples must be taken from that level which is reached by the roots of the particular species.

In order to find evidence for the fact that in the presence of oil bitumen plants enlarge and exhibit other changes, the geobotanists of the All-Union Aerogeologic Trust numerous times measured plants individually by species. From 50 to 100 individuals of each species were measured in each section. It was necessary to measure individuals which were in approximately the same stage of development. For example, in one of the bitumen-bearing sections which we studied, the greatest part of Anabasis aphylla L. had an oppressed appearance: the plants were short, had numerous yellow leaves, and made an attempt to blossom only in September. The rest of the Anabasis aphylla L. plants in this section were of an enormous size and bore an abundance of fruit. It is obvious that the total measurements, as they were usually conducted, would have provided an extremely varied and untrue picture of the size of the hypertrophical Anabasis aphylla L. plants. In these instances, individuals in the same development stage were measured separately.

Data obtained from the measuring were averaged into groups and presented on a table. Tables of measurements for Salsola foliosa may serve as an example (tables 1 and 2).

TABLE 1

Groups of measurements in centimeters (height)	Number of Salsola foliosa individuals	
	Bitumen-bearing section	Control section
10-20	-	-
20-30	-	4
30-40	-	10
40-50	-	-
50-60	7	11
60-70	12	-
70-80	2	-
80-90	3	-
90-100	1	-
100-110	-	-

TABLE 2

Groups of measurements in centimeters (diameter)	Number of Salsola foliosa individuals	
	Bitumen-bearing section	Control section
0-10	-	15
10-20	-	10
20-30	-	-
30-40	-	-
40-50	-	-
50-60	-	-
60-70	-	-
70-80	1	-
80-90	5	-
90-100	5	-
100-110	6	-
110-120	2	-
120-130	3	-
130-140	1	-
140-150	2	-
150-160	-	-

A graphic presentation even more clearly illustrates the size ratios between "bitumen" plant forms and the normal forms.

The dotted graph (figure 3) simultaneously presents the height and the diameter of each individual measured.

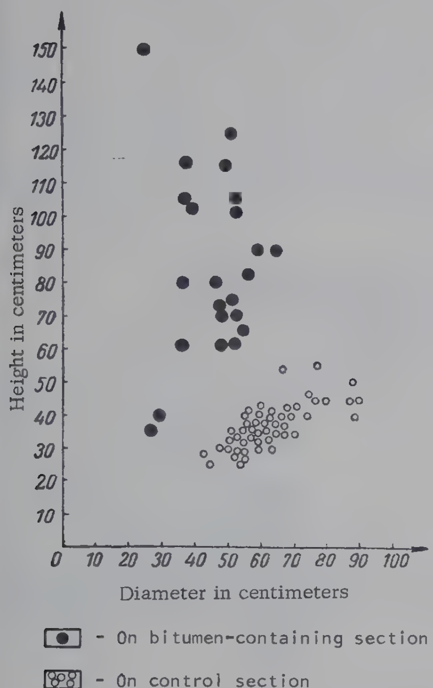

FIGURE 3. Dotted graph showing the size ratios of Atriplex cana grown on bitumen-containing section and on a control section

Diameters of the individual plants are shown on the abscissa and their height on the ordinate. Location of dots indicates the bulk of the individual.

The average dimensions (the mean of all measurements of one species) may very conveniently be compared on a diagram, such as the one illustrated by Figure 4.

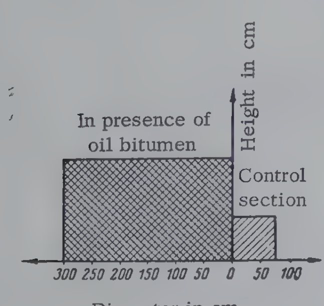

FIGURE 4. A diagram of the size ratios of Anabasis aphylla plants when grown on soils containing oil bitumen and those Anabasis aphylla plants which were grown in the control section

Here toward the right side on the abscissa is presented the value for the mean diameter of the individual from the control section, toward the left the value for the individual grown in a bitumen-bearing section. Ordinate indicates the height. The rectangles obtained in this manner show the dimensions of the plant, the ratios of the diameters and of the height, and the kind of change which occurs in a plant in the presence of bitumen (in this instance the diameter of Anabasis aphylla increases proportionally more than does the height, thus changing the appearance of the plant).

Finally, in order to compare a certain specie on several sections, it is convenient to use curves for the height and diameter measurements.

The groups representing measurements are presented on the abscissas, the number of individuals in each group are shown on the ordinates. (figures 5 and 6).

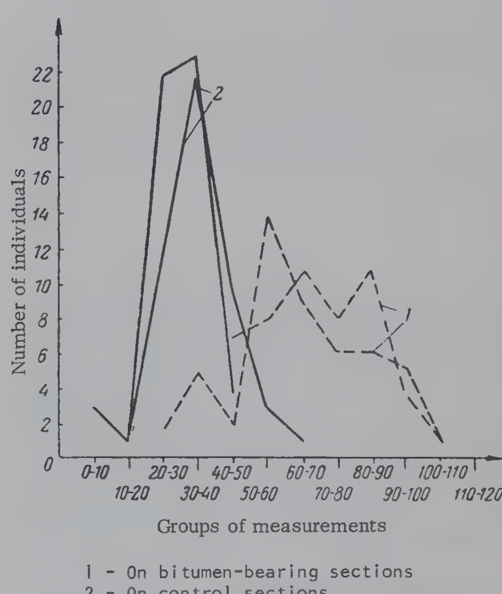

FIGURE 5. Height of Suaeda physophora seepweed in the presence of oil bitumen and on the control section

In the year 1953 geobotanists from the All-Union Aerogeologic Trust on the Uzboy expedition marked areas with increased bitumen content by using as a basis for this work accurate quantitative accounting of the occurrence of geobotanical bitumen indicators. Value representing the occurrence was expressed as a percentage ratio of areas on which plants indicate bitumen content to the total number of areas studied. This technique was used by the geobotanists of the Uzboy expedition in the separation of bitumen-bearing areas.

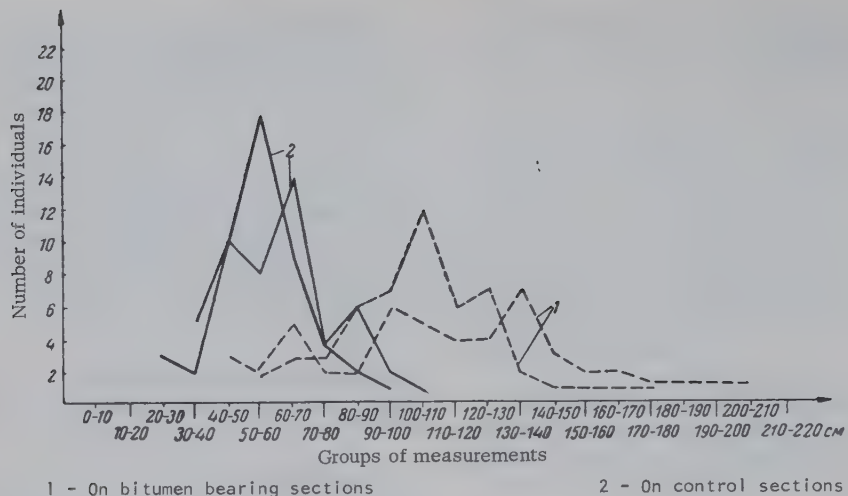

FIGURE 6. Diameter of Suaeda physophora

The work progressed in the following order. A group of geobotanists, in order to detect dispersed bitumen content in the soil, set up a preliminary prospecting grid over the entire territory. The plant cover along the routes was continually observed. Those points were marked on the map where even one single giant specimen, a two-cycle development or a deformed plant was found.

Then all plants which had the above mentioned forms indicating the presence of bitumen for these points were recorded. To accomplish this, 25 to 50 small sections measuring about 1 meter square were outlined in a limited area and all unusual forms of plants observed in each section were recorded. From the data obtained, the occurrence of these plants was immediately converted into percentages. If the occurrence was sufficiently high (usually higher than 10 percent, a drill hole was placed in that section in order to obtain samples for the determination of the bitumen content.

Points with the highest occurrence most frequently were concentrated in a certain area, and the periphery of the area usually contained points with a lower rate of occurrence. A map prepared in this manner accurately showed the area where the geobotanical indicators of bitumen were most common. If the results from analyses are compared with the occurrence of geobotanical indicators, a significant relationship between the bitumen content and the occurrences of geobotanical indicators becomes apparent. This is clearly illustrated by Table 3 (bitumen content is presented in conventional units: the length in mm of bitumen extract line remaining on filter paper extracted from a known rock sample; the geobotanical bitumen indicators were necrotic, i. e., individuals which showed the signs of dying, succulent perennial halophytes Holocnemum

TABLE 3

Number of the description	Frequency of occurrence of geobotanical bitumen indicators in percent	Bitumen content (length of extract in mm)
1121	Less than 5	Traces
1104	12	4
949	12	3
953	36. 5	5
1122-1124	70	7

strobilaceum M. B. and "karabarak".[3]

By contouring the areas where the occurrence rate for geobotanical indicators is the highest, it is possible to identify territories with a high, dispersed bitumen content.

The distribution of geobotanical bitumen indicators in one of the large solonchak basins of Central Asia gave the following picture. On the peripheries of a plateau-like elevation surrounding the basin the plant cover contained numerous Salsola chiwensis plants which were of a giant size and had new pathological forms in the shape of unique "brushes" formed by short, deformed, closely jointed branches. The occurrence of these specimens ranged from 20 to 50 percent. Nanophyton erinaceum plants also were of unique shape and were abundant on the slopes of the basin. Ordinarily these plants have the appearance of ground-hugging cushions or small bushes, but the individuals growing in this section were

[3] Local plant name; not identifiable.

rather tall (up to 30 cm), trim plants with a straight, well-formed main stalk, upward-growing branches and no lateral branching. The occurrence of these forms on the slopes ran 80 to 100 percent. Finally, on the bottom of the basin there was a copious dispersion of pathologically altered specimens of Holocnemum strobilaceum, karabarak and other halophytes. Their occurrence here ranged around 20 percent. Such a rare concentration of many altered forms in a comparatively small area led to the identification of this basin as a section with increased bitumen content, a conclusion fully confirmed by later analyses (table 4).

TABLE 4

Association	Bitumen content (length of sample in mm)
Association with predominance of deformed Salsola chiwensis specimens (section 1).	43
Association with predominance of deformed Salsola chiwensis and Anabasis depressa individuals (section 2).	48
Association with predominance of deformed Karabarak individuals.	5

Different methods for solving this very same problem were used by the geobotanists of an aerogeologic expedition in the regions along the northeastern shores of the Caspian Sea (D. D. Vyshivkin and M. S. Kasyanova). For the purpose of locating prospective bituminous sections, they did not use special small sections to compute the occurrence, but instead used ordinary geobotanical field descriptions. One of the essential elements for geobotanical descriptions is the division of the plant cover into graded classes, i. e., (classification of plants into groups according to their height) with notations as to the group to which a plant belongs. Geobotanical descriptions also usually indicate the phenologic state for each of the species encountered, i. e., the condition in which the plant is found at the time of the description (the beginning stage of blossoming, blossoming, drying up, etc.). These two indications were found to be most important for the detection of the presence of bitumen.

From a systemetic review of the geobotanical descriptions it was easy to separate those points where one or another plant was taller than the range specified for the class in which it usually belongs. This served as an indirect indicator of the fact that plants in this particular section had unusual dimensions and the researcher could immediately separate the sections which should be sampled for bitumen.

An example illustrates the point. It was noted that Kochia prostrata, which ordinarily belongs to Class II, in this section belonged to Class I, which was the very tallest plant group and included tall bushes. The same thing was also noted for the Salsola rigida plants. Such an abnormal classification of two very common species gave reason to believe that these individuals grew tall due to the presence of bitumen. An analysis confirmed this assumption by showing that soil here contained 0. 009 percent oil bitumen.

Phenologic data from geobotanical descriptions, i. e., information pertaining to the different development stages of individual plants, may be used in a like manner. By reviewing the descriptions and separating all sections where plants blossom in late fall, it is possible to mark areas promising for bitumen. Thus, a description prepared during the latter part of September mentioned Caragana frutescens bushes which were in full bloom and those which were just beginning to blossom. Such a late blooming appeared to be highly unusual, since according to the majority of descriptions, Caragana frutescens at this time was already past the blooming stage. The presence of bitumen which evidently could produce great changes in the time periods of plant development was considered as one possible explanation of this phenomenon (Khokhlov, 1947). This assumption was confirmed by analyses which revealed 0. 006 percent bitumen.

In summarizing the methods used for the separation of areas with an increased bitumen content by geobotanical data, it may be concluded that the most effective and accurate technique of prospecting for bitumen is a special geobotanical preliminary survey or a study which uses the occurrence rate computations. However, even in an ordinary geobotanical mapping when descriptions are carefully considered, a detailed study made of the classification of plants into groups according to the size, and of the peculiarities in the development stage of each spècies, it is possible to separate approximate locations of areas containing bitumen.

At this time the technique for the utilization of geobotanical indicators in prospecting for oil bitumen is not fully developed, and its successful application in the future will depend upon the mutual efforts of geobotanists, petroleum geologists, biochemists, physiologists and those working in related branches of science.

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GEOBOTANICAL INVESTIGATIONS IN PROSPECTING FOR ORE DEPOSITS[1]

By

N. G. Nesvetaylova

translated by Gaida M. Hughes[2]

ABSTRACT

The use of plants as indicators in prospecting for minerals is discussed on a broad scale from the standpoints both of available literature and field experiments. The method of isoline mapping of mineral deposits by means of metal content in ashes of plant parts is detailed. The author cautions against too broad use of any single species as a "direct" indicator or too heavy reliance on ash content, as some species tend to concentrate certain minerals, regardless of soil composition. Instead, a combination of species as indicators and a combination of factors, such as appearance of leaves, luxuriance of the plant, and color and time of blooms is recommended. The tendency of some minerals to nullify the effect of others—iron counteracting the effect of copper, for instance — is noted, as well as different effects on plants of different salts of the same mineral. In spite of these qualifications and the early stage of development of this technique, the method has particular merit in areas where the strata overlying the metal-bearing deposits is relatively thick. Analyzing the ash content of leaves of deep-rooted trees is particularly helpful in detecting the presence of an ore mineral in such a situation. --A. Eustus.

* * *

The relationship which exists between the distribution of plants and the geologic structure of the territory is obvious. Of great interest are numerous attempts to utilize plants as indicators in prospecting for some useful deposits, especially ore deposits.

Metals play an important role in the life of plants: some of them are necessary elements for the existence of plants, and may influence the distribution of certain plants; others, being poisonous, cause considerable disturbance in the metabolism and, as a result, various biological and morphological changes may occur. Sometimes the influence of metal upon a plant is so strong as to produce new forms.

This connection between plants and definite properties of rocks is well reflected in ancient folk beliefs.

Thus, in Europe a nut tree (European hazelnut-Corylus avellana), a buckthorn (Rhamnus) and a mountain ash (Sorbus) were believed to indicate deposits of ore and precious stones (Kerner, 1903). In Russia, fir, spruce, and pine were considered to be indicators of placer gold (Karpinsky, 1841). In Brazil it was believed soil that contains diamonds (Spix and Martius, 1823-1828).

A long time ago, some investigators noted changes in the vitality of plants which grew over ore deposits. In 1793, M. V. Lomonosov wrote in his article "Ore deposits and veins and prospecting for them" that grass growing over veins is usually finer and less luxuriant.

The adaptability of Viola calaminaria and Thlaspi calaminarium, the so-called "calamine plants", to zinc-bearing rocks is well known. Ashes of the Thlaspi calaminarium plant (found near Aachen) were discovered to contain more than 13 percent zinc, which comprises 1.5 percent of its dry weight, i.e., several times more than the average quantity of zinc-bearing species which are related, but growing on soils which do not contain any zinc in the substrata. Changes in the soil composition evidently produced the new species. Viola calaminaria must be an altered Viola lutea on zinc-bearing soils.

It is also known that Asplenium adulterinum and A. serpentinum are strongly adapted to serpentinite. Evidently, these particular species of fern developed over serpentinite under the influence of magnesium. This is further emphasized by experiments of Sadebek, who in 1871 cultivated serpentinite fern, Asplenium adulterinum and A. serpentinum on soils which did not contain even traces of serpentinite. In the sixth generation he observed that these species lost their characteristics and turned into common, widely prevalent species of Asplenium adiantum nigrum and A. virida (Varming, 1902, p. 53). Carnations (Dianthus capillifrons) and two species of house leek, Sempervivum pittonii and S. hellebrandtii (Nevole, 1926), are also adaptable to serpentinite. A. Ye. Fersman (1930, p. 219), while studying the geology of the Elba Island,

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[1]Translated from Geobotanicheskiye issledovaniya pri poiskakh rudnykh mestorozhdenii: in symposium volume Geobotanicheskiye metody pri geologicheskikh issledovaniyakh [Geobotanical methods for geologic investigations], Trudy Vsesoyuznogo Aerogeologicheskogo Tresta [All-Union Aerogeologic Trust], Ministerstva geologii i okhrany nedr, No. 1, pp. 118-134, Gosgeoltekhizdat, 1955. Reviewed for technical content by Herbert E. Hawkes, Jr.

[2]U.S. Geological Survey.

also noted great differences between plants growing over serpentinite and those growing over granite. "One does not need to be a botanist to notice this purely external difference," he wrote.

In Australia, Polycarpea spyrostyles was used with great success by geologists in prospecting for copper (Baily, 1889). Special connection was also found to exist between heavy metals, particularly copper, and some mosses; for example, Gymnocolea acutiloba, Cephaloziella (Braun-Blanquet, 1928), and in the Andies, Mielihchoferia and Scopelophila [Scopolia?] (Morton and Gams, 1925).

A very high copper concentration in substrata evidently creates unfavorable conditions for plant life. Thus, in the areas of copper deposits, in Kazakhstan and Rhodesia, plant life is totally absent. Barren areas which are surrounded by plants are considered by prospectors as indicators of possible copper deposits (Vasilyev, 1933).

The outcrops of platinum-bearing rocks, in South Africa and in the Urals are found by the total absence of plant cover (Linstow, 1929; Brudin, 1948).

In New Caledonia (Le Jolis, 1861), certain plants, Dammara ovata, Eutassa intermedia and Dacrydium caledonicum, are adapted to rocks rich in iron content. In a monograph on the vegetation of Armenia, A. K. Magakyan (1941) writes that the vegetation over iron-bearing substrata greatly differs from the vegetation growing over limestone, other sedimentary and nonmineralized vulcanic rocks. While mapping the distribution of Lower Cretaceous iron-bearing rocks in the region of the Zasurskiye forest, the geologist P. A. Ososkov (1896) widely used the vegetation as an indicator of these rocks.

A very high iron content in the soil evidently is harmful to plants and makes their existence impossible. Thus, in areas of ironblende and pyrite deposits in upper Italy, large areas are completely bare of plant life (Braun-Blanquet, 1928, p. 162).

There is a complete group of lower plants, iron bacteria, among which are those which are adapted exclusively to an environment rich in iron (Vinogradov, 1952; Molisch, 1910). Finally, some algae are so sensitive to iron that Ye. Ye. Uspensky succeeded in separating those dominant organisms which indicated not only the presence of iron in water, but also the iron content. In a medium with an overly high iron concentration algae exhibit certain morphological changes, such as unusually large green cells produced by disturbances in the cell division as a result of iron poisoning (Uspensky, 1925).

As mentioned by Krusch (1914), in Bohemia, Trientalia europaea serves as an indicator of tin-containing rocks.

Silver ore deposits in the state of Montana were discovered by the distribution of Eryogonum evalifolium plant (Linstow, 1929).

Literature contains numerous references to the relationship between vegetation and lead, but unfortunately these references are very general and do not provide specific information. A unique growth of some grasses has been noticed in areas rich in lead deposits (Fersman, 1939). In the U.S.A. a plant called "lead grass" is found near lead deposits (Brudin, 1948). The ashes of a number of plants are known to contain lead. "Lead grass", whose ashes contain as much as 3 percent lead, is considered a concentrator (Tkalich, 1938, p. 15). In the experiments of M. N. Tsetsura (1948) on the influence of lead nitrate on the development and yield of sunflowers, it was found that a low concentration of lead may increase the germination energy of seeds, but a high concentration, acting as poison, retards germination. This fact was also mentioned somewhat earlier by A. V. Reinhard.

The "manganese flora" includes some plants which accumulate a considerable supply of manganese, and prefer to grow over manganese-bearing substrata: Digitalis purpurea (Uspensky, 1915), Trapa natans, Zostera nana and Fucus vesiculosus (Malyuga, 1947). Manganese content of these plants is quite high — 7.9 to 9.02 percent. Carex hirta (Vernadsky, 1934), evidently serves as a concentrator of manganese.

An entire biochemical "selenium" province in some areas of the western states of North America is characterized by selenium-rich soils over selenium-bearing Cretaceous deposits, and by plants adapted to it. Investigations revealed that some plants which have grown on selenium-bearing soils accumulate from 1,250 to 5,560 mg of selenium per 1 kg of dry weight of the plant, while other plants on the same soil contain only 3 to 45 mg per 1 kg. Plants which belong to the first group (Oonopsis [Aplopappus], Astragalus, etc.) as a rule, are found on selenium-rich soils, and therefore may serve as indicators of selenium-bearing bedrocks (Beath, 1935; Stayls, 1949).

A. P. Vinogradov (1952, p. 19) mentions the existence of lithium flora (Thalictrum, etc.), sulphur, and also "aluminum plants" (Lycopodiales [Lycopodium?] Ericaceae [Erica?], etc.), the distribution of which depends upon substrata containing those elements. He also mentions a change in the flora of alum lakes on laterite soils in volcanic regions. Vinogradov made some interesting observations of vegetation over some deposits — "During our work in the Southern Urals", he writes, "in areas of copper, chrome

nickel and zinc deposits, and where these elements are dispersed in the soil, we found numerous changes in the flora composition, morphological symptoms in individual organisms, and an increased content of these elements in the bodies of plants".

An excess of certain metals in the soil frequently causes considerable, and very noticeable changes in the external appearance and in the development cycle. These characteristic changes, as well as specific disease of plants, may serve as indicators of the presence of certain metals. For example, the external appearance of plants changes greatly under the influence of manganese. When manganese salts or waste products from manganese production are used as fertilizer, corn and vegetable crops may be increased several times (Khalizev, 1934). Plants nourished with manganese are larger in size and luxuriant in appearance. These phenomena occur not only in agriculture. Geologists who work in areas of manganese deposits have reported an unusual appearance of plants growing over manganese-bearing substrata (Vernadsky, 1934, p. 309).

Finally, addition of manganese to the soil in asters and carnations produces blossoms of a brighter color and changes the color of the almond corolla from white to pink. Other elements are capable of producing similar changes in the color and appearance of flowers. When alumo-ammonium alum or iron salts are added to the soil, pink hydrangea turns blue. An excess of zinc produces changes in the leaves and blossoms of some plants, and the color of blossoms becomes bright yellow or red. By adding copper shavings to the soil horticulturists have succeeded in developing a light blue-colored rose.

Much interest has been created by N. A. Bazilevskaya's experiments (Bazilevskaya and Sibireva, 1950) where the color of flowers was changed under the influence of various elements (manganese, zinc, copper, aluminum and some others). She found that under the influence of each metal the experimental plants ran the gamut of color shades of a definite tone; for example, the presence of zinc salts in the soil invariably was indicated by the change of corollas of flowers into lemon yellow, etc. Changes were also observed in the color of leaves. Under the influence of boron, leaves became dark green; manganese produced light green leaves; copper, very light, almost dove-colored (bluish). An experiment with copper sulfate produced dwarf plants (half of normal proportions).

When salts of several metals were fed simultaneously, the color of flowers also changed, but in variations different from those observed when each of these elements was introduced separately.

Plants frequently suffer from specific diseases, when there is an excess or a deficiency of some metals in the soil. Diseases caused by an excess of manganese are well known (Vinogradov, 1952). The appearance of chlorosis in pineapple may be cited as an example. An excess of boron, introduced by watering the plant, causes leaves of citrus plants to fall (Pryanishnikov, 1940). D. P. Malyuga (1950) observed in the areas of nickel deposits in the Southern Urals that endemic diseases in plants are produced by an excess of nickel.

Literature is by no means complete, but the available data indicate that the great number of observations accumulated suggest the possibility of establishing an auxiliary geobotanical method to be used in prospecting for ore deposits; i. e., a method whereby the plant cover as a whole, plant associations or individual species would serve as indicators of ore deposits.

The biogeochemical method presents another approach to the utilization of plants in prospecting for ore deposits.

At this time it has been proved that there are almost no elements, not even the very rare ones, which would not be present in the ashes of some plants. Therefore, one should not conclude solely on the basis of finding some elements in the ashes of plants that an ore deposit is present. First of all it is necessary to consider the quantitative ratios of these elements. Chemical composition of plant ash is so constant that it may systematically serve as an indicator of a genus or species. This constant chemical composition may change considerably, depending upon the concentration of elements present in the soil.

Most of the plants in areas of ore deposits show in their ashes an increased content of certain metals. By plant ashes it is possible to map contours – if not the very location – of the deposits, then of the halos of dispersed weathering products of mineralized rocks. However, it is known that different plant species absorb elements from the soil in different proportions. Such plants are capable of storing considerable quantities of certain metals. Thus, the ashes of corn kernels grown on andesite soils of Oslani (Slovakia) which contained $2.10 - 5.10^{-2}$ percent gold contained as much as 6.3×10^{-3} percent gold per unit of dry weight; ashes of Equisteum palustre contained 6.3×10^{-2} percent, and the ashes of Equisteum arvense – 6.3×10^{-3} percent. It is interesting to note that the industrial gold content in rocks is 2×10^{-3} percent (Kirsanov, 1936).

It is mentioned earlier that an increased selenium content was found in the ashes of some Astragalae which grow on selenium soils of North America. These Astragalae not only store selenium in their bodies, but grow exclusively on selenium containing soils.

Buckwheat is a concentrator of copper, peas a concentrator of boron.

S.P. Aleksandrov (Fersman, 1931) was the first to use plant ash composition as an indicator in prospecting for ore deposits. While studying the radium deposits in Ferghana (Central Asia) he discovered a high uranium and vanadium content in plant ashes.

In the vast forests of Northern provinces of Sweden, Brundin and Palmquist (Fersman, 1939) prospected for the deposits of gold, vanadium, molybdenum, tin, and some other metals by using as a guide the content of these elements in plant leaves.

S.M. Tkalich (1952, p. 663) rather extensively developed the technique for using the ash method in prospecting. Therefore his work will be discussed in more detail. "Prospecting lines are drawn 20 to 250 m from each other transversely to the area where the ore body or the ore-bearing zone of formation is assumed to be located. Ten grams of leaves of the same prevalent species of the area are collected along these lines at 25 to 100 m intervals". Results from the leaf-ash analysis for the metal sought were marked on a map, which enabled the tracing of isolines for equal concentration of the metal. It is thus possible to determine the dispersion halos of the metal, and to determine its relative content in different parts of the area studied. Using this method Tkalich succeeded in outlining the contours of the Unashinsky arsenopyrite deposits. According to Tkalich, in using the biochemical method in prospecting for various ore types, special attention should be paid to the iron content in plant ashes, particularly in areas of heavy alluvium, since iron in the upper level of porous deposits is more capable of forming water-soluble compounds than are other metals and is absorbed more by plants.

In 1938 Tkalich used beach grass (Calamogrostis), in 1952 birch (Betula verrucosa) leaves and fir needles for ash analysis. Tkalich (1953) expressed the opinion that the iron content in plant ashes makes it possible to determine not only the presence of iron-bearing rocks, but also some other rocks rich in sulfide content. Ash analyses showed that the iron content of plants over ore deposits averaged 5.7 times higher than in plants outside this area.

Iron is usually present in polymetal and sulfide deposits and in the oxidation zone produces water soluble compounds which may be absorbed by plants. Iron, being an element necessary to plants, is accumulated in the plants in very large quantities. The ratio of copper and iron found in the ashes of leaves showed that it is possible to prepare geoindicating schemes for sulfide deposits by the iron content alone. "By determining the iron content in the ashes of birch leaves found in one area of copper-bearing ore deposits, it was possible to outline very accurately the boundaries of this zone and to solve some other problems pertaining to ore-bearing deposits. By determining the iron content in the ashes of plant leaves, it is also possible to determine the relative concentration of this element in the rocks beneath plants, and to make predictions as to the distribution of given rocks under the alluvium" (Tkalich, 1953, p. 94). According to Tkalich (1952, 1953), plant ashes may serve as indicators when the thickness of deposits covering the ore bed is not greater than 5 meters. He prefers the biogeochemical method of testing for iron because such tests are easier to conduct in the field than are complex analyses for rare and dispersed elements.

Lately there have been numerous attempts to utilize the biogeochemical method in prospecting for ore deposits.

While surveying the Novo-Akkermanskoe cobalt and nickel deposits, D.P. Malyuga (1947) came to the conclusion that "the concentration of nickel and cobalt in the soil and in the plants is closely related to nickel and cobalt deposits, and may serve as an indicator in prospecting for these ores. He believes that by using this method it is possible to outline the contours of deposits which are buried at a depth not to exceed 20 to 30 meters.

At the conclusion of this brief review, mention should be made of several studies in British Columbia (Warren and Howatson, 1947; Warren and Devault, 1949, 1950 a and b) on the prospecting of copper, zinc, boron, manganese and magnesium (the latter being associated with ore bodies). These authors used the bark, branches and leaves of plants as a material for ash analyses. They found that best results are obtained from leaves and young branches, and that it is best to use trees which are most common in a given area and which have a long root system (willow, for example). Leaves, gathered in the areas over deposits, contained 3 times as much zinc and 5 to 200 times as much copper, as did the leaves which were gathered in other areas. This method by the authors is considered as applicable in glacial areas when prospecting for zinc. Recently there have appeared the publications by Thyssen, Rankama, Harbough, Babichka and others (Smirnov, 1954), on the utilization of the ash method in prospecting for useful ore deposits.

A.E. Fersman (1939) considered the biogeochemical method to be extremely interesting and promising, and thought that it would be of great practical value in the surveying of some ore deposits.

Modifying somewhat the classification of Tkalich (1952), all known biological methods used in prospecting for mineral resources may

be classified as follows:

I. Methods of "direct" indication

1. Botanical methods

a) utilization of "universal indicators

b) utilization of "local indicators"

c) utilization of all changes in the appearance and development of plants.

2. Biogeochemical methods

II. Methods of "indirect indication".

A brief review follows of all the above-mentioned methods which are used in prospecting for ore deposits.

We will begin with the method of "universal indicators". The term "universal indicators" is applied to plant species distributed exclusively in rocks or soils with a definite mineral content and not found under any other conditions.

In this category are calamine violets and fanweed (Thlaspi), adapted to rocks rich in zinc content; some species of Astragalus, which grow on selenium-bearing soils, some mosses which grow on soils over copper-bearing substrata, and some other plants. These are very precise indicators but their utilization in prospecting for mineral resources presents some problems. The greatest difficulty is the small number of known, reliable "universal indicators", and the limited distribution of some of them. The first step toward an improvement of this method would be to increase the number of "universal indicators" by comparing the data on the indicative value of different species.

The method of "local indicators" uses common, widely distributed plants which may serve as indicators of certain properties of the soil and rocks in some local situations.

Trientalis europeae is an example. In the Soviet Union it is rather widespread and mostly is found in spruce, fir, and cedar forests; in Bohemia, according to Krusch (1914), it serves as an indicator of rocks containing tin.

In the Rudnyy Altai ore deposit regions this author studied "local indicators". We believe that this type of study should be begun in areas which are beforehand known to contain deposits, but where the deposits have not been mined, or where the mining work has been begun only recently, so that the natural plant cover has suffered a minimum of disturbance.

First a detailed study is made of the floristic composition of the plant cover in the entire area, as well as a comparison of complete flora listings compiled not only for the mineral-bearing zone, but also for surrounding area, and a comparison of the coefficients of occurrence and coefficients of community.

Comparisons should be made in rather large, ecologically homogeneous areas. Working in the mountains it is very important that the following conditions be identical: absolute altitude, location in relief, exposure and steepness of slopes, thickness of soil cover, moisture, and other factors.

It was noticed that in mining areas Gypsophila patrinii was often found around ore deposits and refuse ore of mineralized rocks. In studying the ecology of this plant it was first necessary to determine whether or not the distribution of a given specie depends upon the mineral content in rocks, and whether a mineralized substrata is an absolute requirement for the growth of this species. A detailed study of 50 km^2 was made and a map was prepared to indicate the distribution of the specie. Investigators on foot recorded all sections where that particular specie was found (associations where it was the dominant species, distribution of individual plants, etc.).

The map prepared on the basis of geobotanical information then was compared with a map of the known ore deposits and a map prepared from sampling the bedrock and soil. This comparison determined the further course of the study. A detailed description of vegetation was made in every section where this specie was present (other species and their abundance by the Drude scale) and a study was made of the projected cover, height, vitality and phenological conditions.

Special attention was devoted to the general habitat, color of blossoms and leaves, the time and type of blooming, etc.

Descriptions were made by profiles, in order to determine the nature of changes in the plant cover as a whole and in the indicator specie, as they occurred in relation to the increasing distance from the area of "maximum mineralization" (this is very often the outcrop of highly mineralized rock from which the indicator specie is "spreading" down along the slope following the course of the talus slope from the outcrop). A comparison of descriptions of Gypsophila in various parts of the profile with the data obtained from sampling and chemical analysis of soil and bedrock showed that at different concentrations of the metal in the soil and bedrock the indicator plant has a different appearance, a development cycle and blooming time; in autumn there were differences in time when the plant changed color.

Sampling was done in all sections where the indicator plant was found in order to establish

accurately the relationship which exists between the specie studied and the mineral content in rocks. Whenever possible, samples should also be taken from that horizon of soil which is accessible to the roots and from the bedrock. Sometimes individuals of the indicator specie are found in sections which, according to all indications, are not mineralized. However, a detailed study of the bedrock under these plants usually reveals local mineralization (streaks of malachite) or other barely noticeable indications of mineralization.

The mineralization range accessible to a species is determined by a comparison of the distribution map of the indicator specie with the map obtained from sampling the soil and from analyses of samples taken from profiles which cut across the sections where the indicator grows. Of very great significance is the qualitative composition of the mineral content in the soil horizons on which the indicator specie grows. An answer to this problem may be found in the chemical and mineralogic analysis of the soil.

The study revealed that the distribution of a given indicator specie is related to the rocks which have a definite quantity and a definite type of mineral content. Figure 1 shows the distribution of the indicator specie in a 50 km^2 area, depending upon the mineral content in rocks. It is seen from the illustration that the indicator plant is unequally distributed over the area:

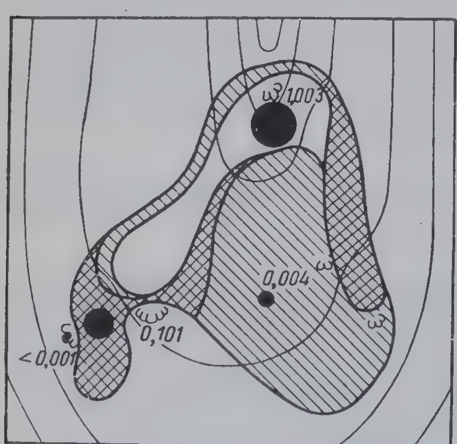

FIGURE 1. Distribution of Gypsophila depending upon the mineralization of bedrock

- area with no vegetation;
- luxuriant Gypsophila plant cover;
- association with the presence of a small number of low-grown Gypsophila plants;
- outcrop of acid effusive tuffs;
- polymetal content in bedrock (in percent)

in the northern part there is an area which is devoid of plants (the total concentration of polymetals here is the highest -- 1.003 percent, copper is from 0.3 to 1.0 percent); lower down on the slope, especially along the shallow hollows of the runoff there is a band of dense cover of luxuriant Gypsophila (concentration of polymetals 0.10 percent, copper from 0.3 to 0.1 percent; the lower part of the slope is occupied by a grassy heteroherbaceous plant cover with only a few low-grown Gypsophila individuals (polymetal concentration is 0.004 percent, copper 0.003 percent). Finally, beyond the area occupied by Gypsophila, a sample of outcropped rock taken at a distance of 1.5 meters from the border of this area revealed in a spectrum analysis a negligible amount of metals – 0.001 percent.

The fact that a relationship exists between a given specie and the mineralized rocks does not by itself mean that it is possible and expedient to use this specie as an indicator of these rocks. A thorough study of the ecologic characteristics of the locations where this specie grows is also necessary. It is also very important to establish the relationship between the indicator plant and the lithologic composition of rocks. If the indicator plant does not grow over a number of rocks, then the possibility of utilizing it in prospecting will be considerably reduced. A study of the areas where the indicator grows and of the associations of which it is a part also presents an important task. This is necessary in order to determine the indicative ability of a given species. It is quite obvious that the indicative value of a specie will be very small if this specie is found only in some definite areas and is adapted to a very narrow range of conditions (if, for example, it grows only in stony or detritus areas). Inasmuch as deviations from the normal form of plants may be used as an indicator of specific conditions of mineralization, it is also necessary to conduct a thorough study of the morphology and biology of the indicator plant's development. Thus, our studies revealed that by a study of the vitality and vegetation periods of the indicator specie it is possible to predict the quantitative and qualitative composition of bedrocks.

A study of the composition of indicator plant ashes is also worthy of attention. According to a preliminary spectrum analysis of the indicator plant's ashes, the plant in its body accumulates a considerable quantity of certain metals. In individual instances the content of these metals in ashes is equal to, or somewhat higher than the content of these metals in the soil, and it is higher than the content in many other plants which grow together with the indicator plant. This is clearly presented by the comparison of data obtained in spectrum analysis.

Number in order	Plant	Copper content in percent
1	Gypsophila patrinii	0.01 - 0.05
2	Festuca sulcata	0. 001
3	Iris ruthenica	0. 005
4	Sedum hybridum	0. 005

These facts may serve as additional evidence of the relationship between the indicator plant and the mineralized rocks.

A great disadvantage of the "local indicator" method is presented by the fact that the regularity with which certain plants or plant associations are adapted to a certain rock in one region may not hold true for another region.

A third method is the method based upon the utilization of all kinds of morphologic and biological changes which appear in the plants when the soil contains an excess of some metal. This method to us appears as the most descriptive, convenient and promising.

Numerous examples were earlier mentioned of such changes as the following: under the influence of certain metals characteristic changes occur in the shape and color of blossoms, in the color and density of leaves, in the ability to bear fruit, etc. Morphological changes may be so significant that they lead to the development of specific species (for example, an ordinary yellow violet on zinc-bearing soil changes into a calamine violet. In this type of studies special attention should be devoted to those members of some plant families (Compositae, Umbelliferae, Rosaceae [Roscoae?] and some others), which are extremely labile and very easily undergo modification when the external habitat is changed.

An excess or a deficiency of some metal in the soil disturbs the natural course of physiological processes in the body of the plant, producing specific changes in the growth rhythm, and may also produce very characteristic plant diseases. This fact may indicate that the rocks contain an excess of some metal.

This method is very convenient because the apparent regularities may be applied to different regions.

The biogeochemical methods, as already has been mentioned, are based on the determination of the mineralization of bedrocks by the content of metals in plant ashes.

The dispersion halos of metals determined by ash analysis and the halos determined by sampling of soils, usually coincide quite well (Figure 2).

This feature is most characteristic for the black earths and similar soils but which contain a large amount of humus. It is know that these soils are able to accumulate metals in their humus horizons. In such instances the biogeochemical method does produce substantially better results than does the sampling method. In podzol soils, red soils, and some other types of soils the metals are constantly leached out from the upper horizons of the soil profile (Sedletsky, 1947). Therefore, according to D. P. Malyuga, "podzol soils cannot be used as indicators of nickel or cobalt (and some other metals as well--N. N.) However, the leaves of trees which grow on these deposits conspicuously concentrate heavy metals and may be used as indicators in prospecting" (Malyuga, 1947).

The biogeochemical method is also invaluable

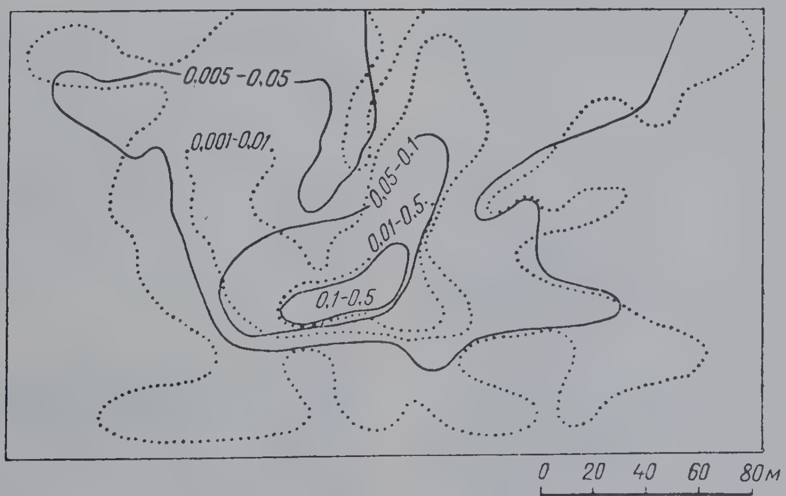

FIGURE 2. Dispersion of lead deposits
Isolines of lead content: - in soil; - in plant ashes

in prospecting for those ore deposits which are covered with such heavy strata of porous alluvium that the ore minerals and their decomposition products do not appear on the surface. While results from soil and ore-slime sampling may give negative findings in this case, the ashes of trees which have a long root system will reveal an increased content of certain metals. Furthermore, utilization of the biogeochemical method apparently is convenient for regions which have great amounts of sediments and especially for regions with dissociated relief.

In utilizing the biogeochemical method it is necessary to compare the content of the metal sought in exactly the same parts of different plants. It is known that the concentration of metals in ashes of perennials is higher than in the ashes of annuals, and in the roots of some plants it is higher than in their above-ground parts (Borovik and others, 1943). The leaves (Tkalich, Warren), and also young branches of trees (Warren and Howatson, 1947) are the most convenient parts for analysis.

In using the biogeochemical method it is necessary to take into consideration the plant's selectivity in absorbtion of different metals. Different plants have a different absorbtion capacity for different elements. In a mass survey the accounting for selectivity will introduce certain difficulties. Using the ash analysis, the most accurate procedure would be to select in all areas only one plant specie; however, this will not always be possible when a large area is studied or when the plant cover is very varied. In such cases in order to somewhat neutralize the selectivity of individual species, it is necessary to use a sample consisting of mixed species from a definite area (an area of 1 m^2 for herbaceous species and 10 m^2 for trees with a sampling grid of a medium density.)

Plants which are concentrators of specific metals may not always be used as indicators of these metals. Such plants store up the metal necessary for their existence in considerably larger quantities than the content of this metal in the soil, and frequently, the rocks on which they grow contain very small concentrations of the metals. Besides, the concentrator plants may be very common in areas outside of the ore deposits. Thus, corn, swamp and field equisetaceae have the ability to store gold, and knot weed stores copper, but these plants are known to be extremely widespread in areas other than gold placers or copper deposits. Only those indicator plants whose distribution is closely related to soils rich in a specific metal content may serve as indicators of these metals. Certain species of the Oonopsis [Aplopappus] and Astragalus genus are this type of indicator, since they accumulate selenium in quantities of 50 and even 200 times larger than all other plants growing together with them, and they can be found only on soils which have a high selenium content. On the other hand, it is obvious that the indicator plants certainly do not have to be concentrators. Such plants, although they do not require a high quantity of the metal for their existence, may prove to be insensitive to the toxicity of this metal. This is particularly true of the plants called "local concentrators".

Finally, there is an entirely different approach to the determination of ore deposits by vegetation and it is based on the method of "indirect indication". In this case vegetation is not used as a direct indicator of the ore-bearing rocks in the area explored. This method, however, will not be considered in this section, since it is discussed in other articles appearing in this symposium.

It is apparent from the above discussion that each of the methods considered has its advantages as well as a number of shortcomings.

It seems to us that in searching for botanical indicators of ore deposits it is necessary to conduct studies in all directions specified. The initial stages of investigations are greatly complicated by the geochemistry and by the physiological influences that various metals have on plants.

Obviously, the effect of one metal will be different for different plants. Various compounds of the same metal will affect plants differently. The soluble compounds of a metal will be more active, i. e., more accessible to the plants. The effect that several metals will individually have on the plant may differ from their combined action. This was confirmed by the experiments of N. A Bazilevskaya (and Sibireva, 1950), who found that by jointly introducing copper sulfate and boric acid into the nourishing medium, different varieties of color were produced in flowers than in the instances where these elements were introduced individually. The presence and concentration of some elements in the soil may determine the amount of other elements the plant will absorb. Thus, Hurd-Karrer (1934, 1935) found that the higher the sulfur content in the soil, the smaller will be the quantity of molybdenum absorbed by plants. Due to this fact if sulfur is present in the ashes of Astragalus, which is a specific concentrator of selenium on seleniferous soils, there will be only a very small quantity of selenium.

Finally, the harmful effect of one metal on plants may be lessened or disappear in the presence of another metal. Thus, the toxicity of manganese may be lessened by molybdenum (Vinogradov, 1950), boron is capable of somewhat weakening the toxicity of manganese and aluminum (Shkolnik, 1952), iron completely eliminates the toxicity of copper (Shkolnik and Markova, 1950), and so on.

In studying the relationship between vegetation and ore deposits this factor should be given serious attention.

Thus, although the methods which utilize botanical indicators in prospecting for mineral deposits are promising, they are also quite complicated and success in the exploitation of these methods depends upon the cooperation of geobotanists, geologists, geochemists, physiologists and representatives from other related fields of science.

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GEOBOTANICAL METHOD IN PROSPECTING FOR SALTS OF BORON[1]

By

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• translated by Gaida M. Hughes[2] •

ABSTRACT

The successful use of geobotanical indicators in prospecting for boron-bearing mineral deposits is described. Three types of indicators were found to apply to three situations where boron is present in varying degrees or combinations with other chemical elements: 1) where boron content is very high, sections may be devoid of plant life or support Salsola nitraria Pall. and Limonium suffruticosum Ktze.; 2) where the magnesium content of ascharites counteracts the effect of the boron, Eurotia ceratoides C. A. M. congregations may indicate sulfate-carbonate soil salinity; and 3) where boron content is in the order of tenths of one percent, plants are oppressed, deformed or subject to plant diseases. A very low boron content, such as on old mineralized banks, on the other hand, stimulates plant growth. --A. Eustus.

* * *

The problem of prospecting for boron is very important and urgently requires a quick solution. The need for the discovery of new boron deposits is dictated not only by the great demands of industry, but also by the ever-increasing utilization of boron in agriculture, especially, as related to the reclamation of virgin soils and waste lands.

The success of geologic studies and the effectiveness of their results first of all depends upon the correct methods used in field work. In order to obtain the maximum of data, geologic prospecting studies must be conducted along with other studies of which the geochemical and the geobotanical are most important.

In 1954 the authors of this article conducted a geobotanical prospecting study for boron and the principal results of this study appear below.

The most important task confronting the geobotanists was to investigate fully the possibilities of utilizing the plant cover in prospecting for borate deposits.

Until this time there were no known geobotanical indicators of boron. However, the information offered in literature suggested that boron has a strong physiological effect on plants under experimental conditions, and this suggested the possibility for the discovery of boron indicator plants.

Investigations during the past years have shown that boron is an element necessary for plant nourishment. Reacting with other elements of the necessary minerals, boron affects the general development of plants by increasing the metabolism in the tissues. Experiments on the influence of boron on plants showed that boron increases the yield and improves the quality of agricultural crops. Therefore, at present time boron is used with great success as a fertilizer for increasing the yield of crops. Very small amounts of boron are necessary for the normal development of plants. An excess of deficiency of assimilable boron in the soils upsets the normal course of physiological processes in plant organisms and produces various plant diseases. A great number of scientific publications have been written on the influence of boron on plants and on its use as a fertilizer (Shkolnik, 1950; Vinogradov, 1952; Katalymov, 1949; Babko, 1938, and others).

However, until now no one has questioned the possibility of utilizing the plant cover as an indicator of the boron content in soils. The close relationship between the plant cover and the habitat, especially soil salinity, and the strong physiological effect of boron on plants encourages the study of such a possibility.

It is known that the boron content in the soil depends upon the boron content in the bedrock. Through numerous experiments it also has been established that plants under the influence of boron undergo a number of morphological and anatomical changes. Therefore, theoretically, it should be possible by the plant cover to learn the boron content in the soil.

In order to solve this problem, it was necessary to study the plant cover in an area which

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[1]Translated from Geobotanicheskiye metody issledovanii pri poiskakh bornogo cyrya: in symposium volume Geobotanicheskiye metody pri geologicheskikh issledovaniyakh [Geobotanical methods for geologic investigations], Trudy Vsesoyuznogo Aerogeologicheskogo Tresta [All-Union Aerogeologic Trust], Ministerstvo geologii i okhrany nedr, no. 1, pp. 135-146, Gosgeoltekhizdat, 1955.

[2]U.S. Geological Survey.

was known to contain boron deposits, and to learn the changes in plants produced by boron.

Geobotanical study in the area of boron deposits was conducted in three directions:

1) search for the plants which would serve as direct indicators of boron;

2) the determination of those signs (changes) in plants which would be utilized as direct indicators of an increased boron content in the soils;

3) investigation of the possibility of utilizing the plant cover as a whole, as an indirect indicator of boron content in rocks.

A study of the morphological and anatomical changes in plants produced by the influence of boron was necessary in order to learn the symptoms of plants which could be used as direct boron indicators. In order to establish indirect indicators of boron, the study was based on the utilization of the plant cover as an indicator of different lithologic or stratigraphic components which contained boron ore deposits.

Plants as Direct Indicators of Boron

In view of the fact that boron minerals are of different chemical composition, and that boron in different compounds produces a different effect on plants, the study of the plant cover was made separately for each type of deposits.

The boron deposit site we studied was associated with the gypsum caprock of a huge ruptured salt dome which was clearly visible on the surface relief. The stratum covering the stony cap was of a rather complex lithologic composition and contained variegated argillaceous gypsum alternating with streaks of grayish-green clays and, in some places, anhydrite and limestone seams. The total thickness of gypsum on this cap varies from 50 to 80 m. On the surface these rocks were covered with argillaceous soil and in some places exposed. Average cover depth was 6 m. The surface elevation studied was a feature of karst topography.

All the known borate deposits on this elevation were adapted to the gypsum cap, especially to the grayish-green argillaceous rocks.

A study of the plant cover in the deposit areas showed that plants did not grow on escarpments[3] and terraces of new open-cut mines. A very luxuriant growth of plants, however, was observed on the banks of older mines and between terraces. This would indicate that boron is leached out from the porous older banks and remains in the soil only in such concentrations as stimulate the growth and development of plants. Boron content in the soil around old mines, according to data from spectrum analysis, comprised fractions of hundredths of one percent.

From studies of the morphological structure of plants growing over boron deposits it was learned that when there is a low concentration of boron in the soil, plants grow 2 to 3 times larger than normally. It was also observed that the diameter of bushes increases and the bushes acquire a spherical shape due to the increased lateral growth of branches. Plants have larger and more succulent leaves and in summer their greener, fresher color stands out against the background of dried-up vegetation. Thus, Kochia prostrata Schrad. on the banks of old mines usually grows in strongly branched bushes which are from 80 to 90 cm tall and 60 to 70 cm in diameter.

In order to learn the influence that boron has on plants, we selected several control sections outside of the boron deposit zone where the rocks contained practically no boron. It was established that on the control section Kochia prostrata Schrad. grows only 20 to 25 cm tall and 15 to 20 cm in diameter.

Artemisia lercheana Web. on the banks produces strong individuals with many stems, attaining a height of 50 cm and a diameter of 30 to 40 cm. An individual here may have as many as 60 to 80 branches. In addition, the plant has a large number of generative shoots and blossoms. It acquires a characteristic greenish-gray color which sets it off against the general background of plants.

In the control section this plant is 10 to 20 cm tall and 20 cm in diameter. The generative shoots are few and poorly developed.

A similar increase in size may also be observed for other plants which grow on the banks of mineralized rocks; Anabasis aphylla, Eurotia ceratoides C. A. M., Limonium suffruticosum Ktze., many saltworts, and others.

Phenological observations of the ore deposit areas showed that plants growing on mineral containing rocks begin to blossom earlier and go through their development cycle more rapidly than plants outside the ore deposits.

The beneficial influence of small doses of boron as mentioned in literature, is confirmed by the characteristics in the development of plants as observed on the banks of old mines.

On the banks of newer mines where boron concentration is higher (in fractions of tenths of one percent), the plants are stunted, become deformed, or easily succumb to diseases. Thus, it has been observed that many plants have a stunted main stem which leads to an increased

[3] Russian original: karyer.

branching of the stalks or the formation of many leaf buds. Such stunted growth was observed for Eurotia ceratoides C. A. M., many saltworts, Anabasis salsa Benth., and many others.

On hydroboracite deposits Anabasis salsa Benth. develops a large, flattened form with shortened internodes, and as a result of this, acquires a unique, abnormal shape. Deformities were also observed in glasswort (Salicornia) and a number of other saltworts (fig. 1).

It was also noticed that on boron-bearing reddish-brown clays many plants acquire a creeping form which they do not have normally; for example, Erotia ceratoides C. A. M., Kochia prostrata, Statice [Limonium] gmelini Willd., and numerous others.

In addition to the above-mentioned alterations, plants which grow on soils with an increased boron content show a heavy pubescence. Thus Salsola lanata Pall. on the banks of mines is so downy that it becomes silvery and may not be recognized.

The leaves of some plants in areas with high boron content first turn yellow and later fall off. In addition, plants in these areas also exhibit increased gall production. This serves as evidence that under the influence of large amounts of boron plants become generally weakened and succumb more easily to disease. Increased gall production was noted for Kalidium caspicum L. Ung.-Sternb., Salsola laricina Pall., and Artemisia lercheana Web. Salsola lanata Pall. on the banks suffers from rotting of the neck of

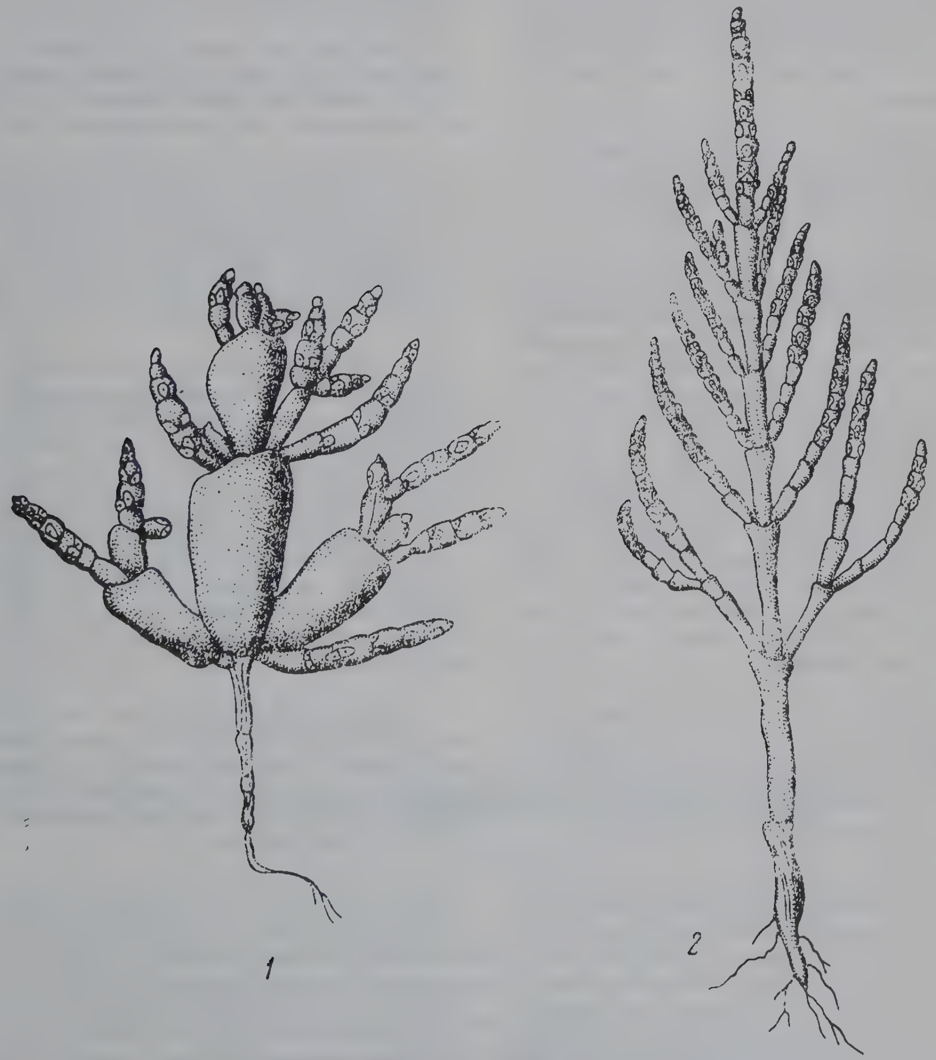

FIGURE 1. Morphological changes in Salicornia herbacea L. under the influence of boron

1 - Salicornia herbacea L. grown on a soil with an increased boron content;
2 - Salicornia herbacea L. grown on control sections which contained practically no boron.

of the roots and perishes before it completes its development cycle.

Investigation showed no vegetation on fresh banks and escarpments. Only a few individual bushes of Salsola lanata Pall. or Limonium suffruticosum are to be observed. The absence of plants on fresh banks and escarpments is due to the destructive effect on plants of large amounts of boron. Therefore, the so-called "bald spots", i. e., areas devoid of vegetation, serve as a prospecting indicator of boron and have been successfully used by geologists in prospecting for boron. Such areas have been observed where borates are close to the surface. However, in using this indication it should be remembered that bare spots sometimes are produced in areas which have a very high sulfate-salts content. Even in such areas we found a plant – Salsola nitraria – which was able to tolerate maximum concentrations of boron and would grow on pure ulexite. It was, however, very oppressed.

On ulexite deposits we also found bushy Statice gmelini Willd., wooly Salsola, and Frankenia in a very stunted condition (their height at maturity was from 3 to 5 cm).

Positive results have not yet been obtained from investigations designed to discover those plants which would serve as direct indicators of boron. Therefore, we devoted special attention to investigations which were concerned with the possibility of utilizing plant associations as indirect indicators of boron deposits. These investigations were based on the fact that the distribution of plant associations is determined by a definite lithologic composition of rocks which, in turn, contain a definite amount of boron. Thus, the borate ores in the area studied, depending upon the qualitative composition of their admixtures, were classified into the following: gypsum, argillaceous, and carbonate ores. Each of these ore groups are related to definite boron minerals.

The above-mentioned ores are situated in the gypsum cap and are covered by argillaceous soil. The detection of these ore bodies is a difficult task for geologists because in most instances they form small, individual lenses which may be discovered only by an uninterrupted sampling of the territory.

In areas where the plant cover is very sensitive to the lithologic composition of rocks and to the type and the degree of soil salinity, the dispersion of the above-named ores is much easier to determine by using geobotanical indicators. Geobotanical investigations showed that a complex of an Artemisia lercheana Web. association and an Anabasis salsa Benth. association were dominant in the area of argillaceous ore dispersion. Plant cover over the carbonate ores is characterized by an Artemisia lercheana Web. association with the presence of Eurotia ceratoides C. A. M., Agropyrum desertorum and grasses (Gramineae). The plant cover over the gypsum ores is composed mostly of an Euphorbia species and Scabiosa isotensis L. association.

Observations of the deposit site and the nature of the plant cover in the area studied showed a general regularity with which the deposits tended to gravitate toward the saline areas of the elevation. These saline sections against the general background of Anabasis aphylla - Artemisia incana association are identified by a complex of Artemisia incana and Anabasis salsa Benth. associations. Some deposits, such as ulexites, are definitely related to the areas of the highest salinity, and are identified by a saltwort plant cover. A more detailed description follows.

Ulexite deposits frequently are located in the lowest part of the territory, close to underground water. Usually ulexite is contained in the grayish-green or grayish-brown gypsum clays.

Due to the proximity of subterranean water and dryness of the air, boron-bearing solution are intensively elevated, and as a result of evaporation, boron becomes concentrated in the upper horizons of the soil. This produces a distended ulexite solonchak which has a solid layer of ulexite at the surface.

The plant cover toward the center of the ulexite solonchak is composed of a Salsola nitraria Pall. association. This plant has an extremely oppressed appearance; at the time of blossoming it is never taller than 8 cm, but the greatest majority of plants attain a height of only 3 to 5 cm. On the peripheries of the solonchak, where ulexite is more deeply imbedded, the plant cover is composed of Limonium suffruticosum Ktze. association. By the saltwort associations ulexite deposits are easy to distinguish against the general background of vegetation.

Limonium suffruticosum Ktze. was also observed by hydroborite deposits where the ore was contained in grayish-green or reddish-brown clay and on the banks of mineralized rock refuse dumps. These plants were not found on any other types of deposits.

Salsola nitraria Pall. and Limonium suffruticosum Ktze. were found exclusively on the outcrops of grayish-green and grayish-brown boroniferous clays. Therefore, Salsola nitraria Pall. and Limonium suffruticosum Ktze. may be recommended as indirect indicators of boroniferous clays in areas of ore deposits, where these very common plants indicate hypersaline clays. It is known that some saline clays contain boron. Therefore, Limonium suffruticosum Ktze. and Salsola nitraria Pall. on deposits and in territories which are likely to contain boron deposits

may serve as orienting landmarks for boroniferous clays without being indicators of boron, itself.

Geobotanical studies over ascharite deposits showed that in most instances the plant cover does not differ from the surrounding vegetation by its floristic composition, but that there are some differences in the development of plants. Artemisia and other plants on ascharite deposits are well-developed and have a fresh, grayish-green color. This may be explained by the fact that the boron effect on plants depends upon the chemical composition of the borate, the extent of its solubility, and the type of soil salinity.

Ascharite belongs to magnesium-type borates but magnesium, according to literary data (Shkolnik, 1950), reduces the toxic effect of boron on plants. Besides, ascharite is a mineral which is not easily soluble in water. According to geologic data, ascharite almost always is related to carbonates (sometimes a complete carbonization of the ascharite deposits takes place). Therefore, geologists for a long time have used outcrops of carbonates and their weathering by products as one of the prospecting indicators of boron. According to literary data (Shkolnik, 1950), calcium decreases the absorption of boron by plants. As a result, the plant cover on ascharite deposits where the ore-bearing rocks include carbonates, usually shows normal development or has a somewhat fresher appearance than do the plants in the surrounding areas.

Geobotanical investigations show that Eurotia ceratoides C. A. M. grows abundantly and is better developed on ascharite deposits.

Eurotia ceratoides C. A. M. is an indicator of sulfate-carbonate soil salinity, and, since ascharites are always connected with carbonates a congregation of this plant may be used as an indirect orienting landmark for ascharite ore bodies.

Besides studying the morphological characteristics of plant structures in areas of deposits and identifying indirect indicators, we also attempted to determine the degree to which plant distribution is related to the mineral content in rocks.

The study of the distribution of plants by geochemical profiles showed that the plant cover changes greatly depending upon the boron content in the soil. Thus, when soil has a higher boron content, an Artemisia lercheana Web. association is replaced by an association of Limonium suffruticosum Ktze., which in turn at a still greater concentration of boron, is replaced by Salsola nitraria Pall. (fig. 2).

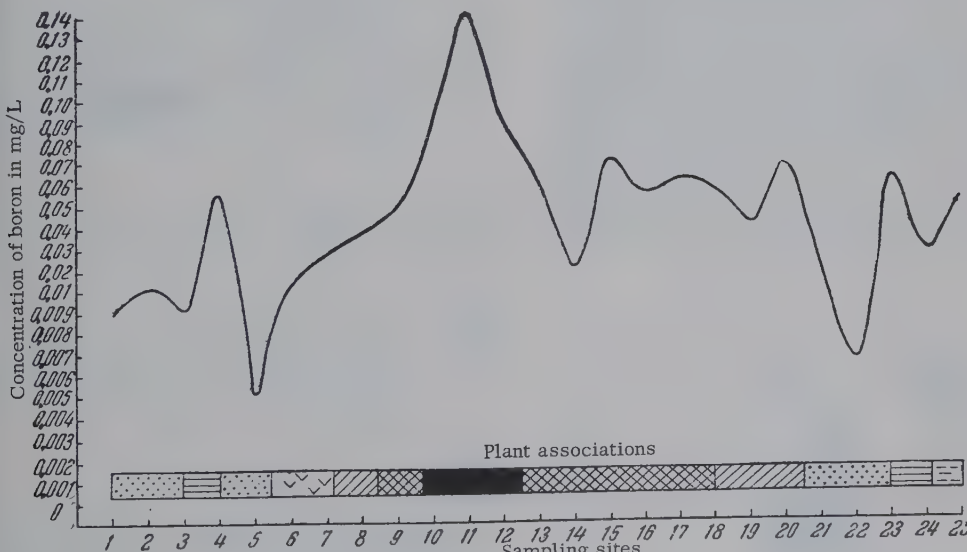

FIGURE 2. Changes in the plant cover at various boron concentrations in the soil

- Anabasis aphylla-Artemisia incana association;
- Artemisia incana-Artemisia pauciflora association;
- "Ebelek" -Artemisia incana association;
- Artemisia incana - Limonium suffruticosum Ktze. association;
- Limonium suffruticosum Ktze. association;
- Salsola nitraria Pall. association
- Anabasis salsa Benth. association.

In this respect, a definite ecologic tolerance range is exhibited by a number of plants. Artemisia lercheana Web. has quite a wide boron tolerance range and grows on soils where the boron content is from 0.008 to 0.06 percent.

Limonium suffruticosum Ktze. has a narrower range, but it is better able to endure boron and grows on soils which contain from 0.15 to 0.5 percent boron. Salsola lanata Pall. and Frankenia also belong to this group. Finally, Salsola nitraria Pall. grows on the highest boron concentrations – on ulexite solonchaks which contain as much as 35.6 percent boron.

Following are the results from geobotanical investigations in one area of boron deposits.

We made an attempt to use the above-discussed prospecting guides in areas where the boron content had not yet been determined.

The area studied consisted of a salt dome structure located several hundred kilometers south of the previously investigated area. This elevation was a ruptured salt dome with gypsum and rock salt emerging at the center. Structurally, this gypsum cap was in many respects similar to the corresponding rocks found in the area studied earlier. In addition, the saline water lakes located on the surface of the salt dome structure had a high boron content. All this information suggested that this elevation might be boroniferous.

A geobotanical investigation revealed that Salsola nitraria Pall. associations were situated on the central and northern sections of the elevation. Limonium suffruticosum Ktze. was also present along the shores of the lakes and was a component of the plant cover. Analyses of water from the lakes located on the elevation showed that Salsola nitraria Pall. and Limonium suffruticosum Ktze. are adapted to the lakes which had a high boron content (fig. 3).

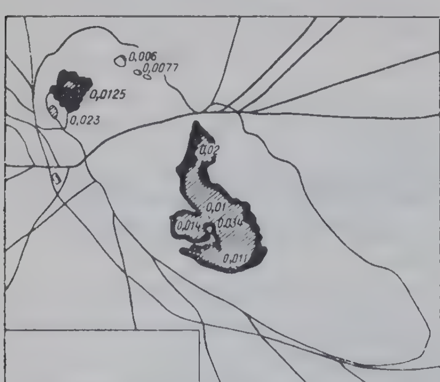

FIGURE 3. Adaptability of Salsola nitraria Pall. to lakes with a high boron content

- lakes with a low boron content;
- lakes with a high boron content;
- distribution of the saltwort Salsola nitraria Pall.

In the southeastern part of the elevation, using of geobotanical information (distribution of Limonium suffruticosum Ktze., anomalies of Anabasis salsa Benth., the increased size of Eurotia ceratoides C. A. M., and Artemisia lercheana Web., as well as bare spots), we outlined a number of sections which appeared to be promising for boron. Spectrum analysis of soils confirmed the boroniferous character of all these sections.

To compare geobotanical information with the data from spectrum analysis of soils, the entire elevation was sampled for boron. Comparison of an outline of surface manifestations of boron, compiled from geobotanical landmarks with one compiled from the data obtained by spectrum analysis of soils revealed a complete concurrence (fig. 4). This confirmed our earlier conclusions as to the feasibility of utilizing plant cover in prospecting for boron.

FIGURE 4. Locations of boron deposits as outlined on the basis of geobotanical information, and areas with a high boron content (data from spectrum analysis of soils).

- areas with a high boron content, determined by geobotanical data;
- sampling points which showed a high B_2O_3 content (from 0.025 to 0.5 percent) in spectrum analysis of soils.

CONCLUSIONS

As a result of geobotanical investigations of areas with known boron deposits and areas prospective for boron, we arrived to the following conclusions.

1. Plant cover may be utilized as an indirect indicator of boroniferous rocks in areas of boron deposits and in areas prospective for boron.

2. On old banks of mineralized rocks where boron content is insignificant (fractions of a hundredth of one percent), plants are well developed because small amounts of boron stimulate growth and development.

3. In sections where boron content is higher that fractions of a hundredth of one percent, plants are oppressed, display deformities, or are subject to diseases (rotting of roots, increased gall content, a yellowing and loss of leaves).

4. Sections where boron content is very high plant life is totally absent. Therefore, sections devoid of plant life may undoubtedly serve as prospecting indicators for boron. Only a few plants tolerate high concentrations of boron; for example, Salsola nitraria Pall. and Limonium suffruticosum Ktze.

5. The investigated boron deposits where ascharites almost always are related to carbonates, Eurotia ceratoides C. A. M. congregations may serve as an indicator of sulfate-carbonate soil salinity, and may be recommended as an indirect, orienting prospecting landmark in areas of carbonate and ascharite ore bodies.

6. Utilization of geobotanical indicators showed that outlines of boron manifestations, prepared from geobotanical information almost completely concurred with the outlines prepared from data of spectrum analysis of soils in areas where the presence of boron deposits was not known previously.

In summarizing the above discussion, we believe that this first work definitely showed the effectiveness of geobotanical studies. Continuation of this work would be of great value because it would verify these results and bring them into more complete agreement with geologic data.

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AEROVISUAL GEOBOTANICAL OBSERVATIONS IN DESERTS AND SEMIARID REGIONS[1]

By

M. S. Kasyanova

• *translated by Gaida M. Hughes*[2] •

ABSTRACT

The techniques of aerogeologic observations and the coordination of such observations with ground studies are described. Some broad distinctions of plant associations are described, notably those including various species of sagebrush (Artemisia), beachgrass (Calamagrostis), Tamarix and various desert grasses. Certain species are best mapped when seasonal color changes occur. The violet bloom of the halophyte Statice suffruticosa, for instance, makes it possible to distinguish saline areas on the Ustyurt Plateau. Aerovisual observation gives the supervisor a chance to check the mapping accuracy of subordinates. --A. Eustus

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Wide use of aerial methods in the preparation of geologic, geomorphologic and geobotanical maps requires that techniques be worked out in detail for each element comprising the aerogeologic and aerogeobotanical investigations.

Aerovisual observations present one of the most important, but at this time methodology-wise still insufficiently developed, links in the application of aerial methods.

Many researchers who have used aerial methods consider them as very important. V. N. Andreyev (1953), a well-known Soviet aerogeobotanical investigator, writes that "the information obtained by aerial photography without supplementary aerovisual observations is dead and incomplete".

Following are the aerovisual observations done by the geobotanists of the All Union Aerogeologic Trust:

(a) aerovisual reconnaisance;

(b) aerovisual mapping routes;

(c) final aerovisual routes.

Aerovisual reconnaisance was used in the beginning of field work, in most instances prior to the field studies on the ground. Its purpose was to give the geobotanist-observer a general idea of the vegetation and the landscape of the area to be studied, and at the same time to provide a picture of how prevalent plant associations visible on aerial photographs look in the location. Therefore it is recommended that aerial photographs or their reproductions on a smaller scale be brought along on reconnaissance flights.

Flying over unknown territories, the observer acquaints himself with the location and conditions of roads, marking those which are least suitable for transportation, notes areas with hard-to-distinguish plant cover, etc. In areas inaccessible for field studies (for example, impassable solonchaks of the Caspian Sea shores and onetime bays of the Caspian Sea (such as Mertvyi Kultuk, Kaydak and Kara-Kichu), the observer marks paths and areas which would be most convenient as on the ground routes.

However, the most important element of reconnaissance is the comparison of the principal sections of the plant cover seen on aerial photographs with their actual position on the ground, and remembering the characteristics of the plant cover and of the territory. Since a thorough recording is not possible during a flight, the observer makes a rough draft of his observations in a diary and on a photograph, which are deciphered immediately upon his return from the mission.

During the time interval between the first reconnaissance flights over the territory and the aerovisual mapping mission, the geobotanist visits those areas where the plant cover could not be distinguished from the airplane. These areas are described in detail and the results of the descriptions are compared with aerial photographs. Thus, characteristics of the plant cover are established.

Aerovisual mapping missions may be used in small-scale geobotanical mapping conducted

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[1] Translated from Aerovizualnyye geobotanicheskiye nablyudeniya v polupustyne i pustyne: in symposium volume Geobotanicheskiye metody pri geologicheskikh issledovaniyakh [Geobotanical methods for geologic investigations] , Trudy Vsesoyuznogo aerogeologicheskogo Tresta [All-Union Aerogeologic Trust] , Ministerstva geologii i okhrany nedr, no. 1, pp. 147-151, Gosgeoltekhizdat, 1955.

[2] U.S. Geological Survey.

to assist in geologic surveying of territories which include large areas of homogenous plant cover. This technique in mapping was widely used in the work on the Ustyurt plateau, in the surveying of some parts of Western Kazakhstan, and elsewhere. In the process of aerovisual mapping mission two observers fly over the territory along predetermined routes. One of them, continually tracing the route on the photographs, marks by symbols the various plant associations seen on the way, while the other logs each entry, so that when the speed and the course of the flight are known, this provides additional information enables the location of each entry on the map to be determined. In an extreme emergency both of these tasks may be performed by a single observer; however, the authenticity and accuracy of the work will suffer.

Aerovisual mapping routes must coincide with ground routes, but they may be less dense if aerovisual observations provide a basis for considering the territory as geobotanically homogenous. It is recommended that ground routes be provided for those areas where the plant cover is difficult to differentiate in aerovisual observation. However, even when the plant cover is very homogenous, it is necessary to supplement aerovisual observations by at least a limited number of observations conducted on the ground.

The color, pattern and shades of the surface of the plant cover as a whole, and the color and form of the crowns of trees and bushes are the most important direct indicators in the mapping of vegetation from an airplane.

Indirect indicators such as the position in the relief, the character of junction with other areas and the size and configuration of the area have also been used with success.

Best results are obtained in aerovisual mapping when the flight altitude does not exceed 200 meters. In semiarid regions during the summer at this altitude it is easy to distinguish even between such homogenous objects as Artemisia - herbaceous associations.

Artemisia produces a light gray background to which the grasses give a yellowish shade. This sign is so permanent and stable that it has been very successfully used by observers. Thus, the following notation appears in one of the aerovisual observation journals of the geobotanical research party No. 10 (Aerogeologic expedition No. 10, 1953): "The chain of small elevations produces an even gray background (Artemisia), which on its northern bend gradually becomes yellow (grasses)."

The same constant pattern and color is also produced by an Artemisia-Anabasis aphylla association. It may always be recognized by the light gray background with green spots produced by scattered Anabasis aphylla bushes.

Artemisia terrae-albae and Anabasis salsa associations are more difficult to distinguish by color. Both of these associations are gray and a certain amount of experience is necessary to differentiate between them. In a careful study, however, even here some differences may be noted. Most often the Anabasis association is of a darker gray, sometimes with steel or greenish shades of gray.

The characteristic pattern of an Anabasis association becomes more noticeable when groups of Artemisia terrae-albae or Salsola rigida grow next to it. To the observer the Anabasis salsa areas appear completely flat, while the Artemisia and Salsola rigida areas are recognized by the taller stature rising above the Anabasis salsa surface.

When small spots of Artemisia or small, completely bare areas appear in the sparse Anabasis cover, then the pattern of such an becomes non-homogenous, spotty, variegated. At a lower altitude it is possible to see every bush.

From an airplane it is difficult to differentiate between herbaceous associations. During early spring all of them are equally green, but during the summer and autumn equally yellow. Therefore, it is not always possible to find the dominant specie. For example, it is difficult to differentiate between Agrophyrum sibiricum, Festuca sulcata and Stipa oapillata, although the latter looks somewhat different due to the "curly" appearance of its sod. Species of the Calamagrostis genus, however, are easily distinguished by the height and broom-shaped form of the plants. After some training one may differentiate between Stipa canillata associations and areas with Agropyrum sibiricum and other grasses by the shade.

In the northern part of the Caspian Sea lowlands, Atriplex cana produces large fields and usually does not form complexes. The Atriplex cana fields from an airplane are notable for their grayish-green color and a uniform, seemingly curly pattern.

Areas where Artemisia scoparia is dominant are brownish-red, especially during the last part of summer and in the autumn when the plant stems acquire the deepest brown color.

On semi-stable sands the vegetation is sparse; therefore, even individual plants may be noticed. Artemisia arenaria usually grows on wind-blown basins and produces a rich green color and an openwork texture. Bushy plants such as species of the Colligonum genus and Tamarix also grow on these sands.

Colligonum overgrowth is notable for its lighter color and gentle, seemingly translucent crowns, while Tamarix is bright green and has a thick, dense crown. When in bloom, the bright green color of Tamarix takes on a lavender hue. During the latter part of summer Colligonum may be recognized by an abundance of red, yellow and orange fruit.

The best time for mapping territories where salworts are dominant is autumn because then the plants turn red and the different shades of red produced by different species are easily seen from the airplane.

Vegetation which surrounds solonchaks is easily seen from the air. By the vegetation it becomes possible to determine the degree, and partly also the dynamics of the salinization. Young solonchaks or those which are undergoing a salinization process, have a border of green, tiny mounds which are composed of Holocnemum strobilaceum plants. Sometimes, next to Holocnemum strobilaceum is detected a narrow band of brighter green Saliconia herbacea which forms an even, dense cover. In the autumn this band turns red. Desalting solonchaks, as opposed to those which are undergoing salinization in, have a border of "Azhrek"[3], which in the autumn is yellow, and of Tamarix which may easily be recognized by the height and the thick green crowns. This sign was successfully used in the Caspian Kara-Kum region.

Moisture-loving vegetation is especially easy to map from an airplane because with its bright green color it stands out against the general background of desert and semiarid region vegetation. Thus, in the gulches of Ak-Tau elevations (Mangyshlak Peninsula), it is easy to perceive overgrowths of reeds which appear as thick, evenly cut brushes, as well as areas with Stipa splendens which produce large yellowish-green fields. The large blossoms of Stipa splendens gives it the yellow shade. In addition, the large sod and the height makes the plant noticeable.

Sometimes in aerovisual observations by the distribution of individual, easily recognized but at the same time ecologically very definite species of plants, it is possible to note rather complex and difficult to detect processes. For example, according to the report by S. V. Viktorov, in Southeastern Ustyurt, it was possible to determine the boundaries of all areas where salinization process was active by the wide distribution of beautifully blooming, characteristically violet color of the halophyte Statice suffruticosa. The appearance of this species in shallow depressions of the plateau (where on nonsaline soil usually would develop Artemisia), served as a true indication of early stages of salinization. This was later confirmed by test results.

In aerovisual observation for a number of species it is possible to distinguish a great number of gigantic plants. Such observations are of interest because it is known that a giant size and deformities in desert plants often are caused by the presence of bitumen.

The above-mentioned mapping guides do not by any means provide a complete listing. Each observer in mapping from the plane should supplement the list of mapping guides and publish them in aerovisual observation journals. Such information is of great value to all persons who would begin a study of that particular area.

The final aerovisual routes are important in field work. Their purposes are varied. Most often they are used either for the purpose of coordinating into a single scheme the great variety of plant associations, or for visiting otherwise inaccessible regions. The first of these is the most important. These routes must be planned in such a manner that they cross all major geomorphological elements of the region, all larger fields of various rocks and the principal landscapes. In such a flight the observer is preparing an enormous profile in which all plant associations are united into one single ecologic order. The observation and interpretation of results in such flights requires high qualifications of the observer.

Finally, aerovisual flights serve as a method whereby the superior may inspect the performance of his subordinates, since a large territory may be covered in a minimum of time and the quality and shortcomings of the work by persons who are preparing the maps, may easily be noted.

Thus, the significance of aerovisual observations already at this stage of development of field studies is serving various purposes, and it is anticipated that in the future they will be utilized even more fully.

[3] Local plant name.

Review Section

CONTEMPORARY SEDIMENTS OF THE CASPIAN SEA[1], a Symposium of papers by M. V. Klenova, V. F. Solovyev, N. M. Arutyunova, P. G. Popov, L. A. Yastrebova, V. P. Baturin, and E. K. Kopylova, 302 pp., published by Academy of Sciences of the USSR, Moscow, 1956. A Review by Robert L. Folk, University of Texas.

The book consist of eight papers, varying from comprehensive surveys of the entire Caspian to detailed local studies. Mainly it reports the results growing out of a survey started in 1945, although some older work is included. Summaries of the several papers follow.

M. V. Klenova, SEDIMENTATION ON THE CASPIAN SUBMARINE SLOPE WITHIN AZERBAIJAN, pp.7-117, 42 figs. 20 tables, 102 refs.

This, the longest paper in the book, begins with a thorough discussion of the geologic structure and origin of the Caspian depression, describes the history of the changes in level of the Caspian, and the different terrace levels formed by these changes. Next the stratigraphy and structure of the complex Azerbaijan coastal area are covered. Composition of the sediments brought in by the various rivers is strongly affected by climate, e.g. the Volga and Ural bring in much dissolved carbonate from the black earth soils. A small amount of wind-blown material is contributed. Fluctuations in the level of the sea, consequently its salinity, are mainly influenced by discharge of the Volga. The chemistry of the Caspian is discussed; it is everywhere oversaturated with respect to calcium carbonate, and greatest salinities are attained on the eastern side. All waters contain oxygen except the deepest holes, for circulation reaches the bottom almost everywhere. Consequently sediments are greenish gray, not black. Regional variation in phosphate and silica content are also discussed briefly.

In the vicinity of Cape Apsheron, submarine erosion takes place on highs, while hollows are filled in with sediment. Sediments are classified and mapped on the basis of percentage finer than 0.01 mm, and the amount of this material correlates in general with the depth of water. Sediments in areas of submarine erosion often show bimodal histograms. The microfauna consists largely of Rotalia and ostracods, but many reworked foraminifera are found; fauna of the deltas are contrasted with those of the open Caspian. Some shallow water forms have been transported into deeper water by "coastal suspensions".

Heavy minerals along the Caspian coast are complex, and reflect local source areas. Triangular diagrams are used to show variations in mineral percentages, and to recognize specific sources. Chemical analyses of the sediments show calcium carbonate most abundant in the east. Manganese content increases with amount of fines, and both phosphorus and manganese increase in the deepest parts and near large river mouths. This section is larded with polemics against earlier Soviet workers, however there is much detail on the changes of chemical composition with grain size, location, etc. These data are used to propose a marine coastal origin for the "Productive Stratum" in Azerbaijan.

This is a competent and detailed work; however, most of the material is of local interest.

V. F. Solovyev, PECULIARITIES OF DIFFERENTIATION OF THE PRESENT CASPIAN SEDIMENTS IN THE REGION OF APSHERON, pp. 118-136, 2 figs., 6 tables, 9 refs.

Boulders and pebbles are produced by erosion of submarine outcrops. Shells and oölites also occur in shallower water, while clays are characteristic of deeper water. Some sliding takes place on slopes of 5 to 7 degrees. Classification and analysis of the sediments is done by inspection of histograms. A brief review of mineralogy, microfauna and chemistry conclude this discussion. The paper is strictly of local interest.

V. F. Solovyev, SOME CARBONATE SEDIMENTS OF THE CASPIAN SEA, pp. 137-150, 2 figs., 3 tables, 13 refs.

After discussing briefly the manner in which calcium carbonate is brought into the Caspian, Solovyev divides the carbonate sediments into three groups: 1) calcite brought in as solid particles (e.g. by erosion of coasts, suspended matter in rivers, or shell abrasion along shorelines); 2) chemically deposited carbonates; and 3) organic tests. Solovyev here pays most attention to the chemical precipitates, further subdividing them into three groups; 1) calcite muds (not studied in detail here), 2) oölitic sands, and 3) irregular crusts.

He reviews in general the factors which cause precipitation of calcite from natural waters, including bicarbonate saturation, temperature, pH and other standard factors. The Caspian is much less salty than the ocean, and is particularly low in ratio of chlorine to the other salts. Calcite is above the saturation point everywhere in the Caspian, even at the bottom, thus precipitation takes place throughout the whole sea but is considerably more intense in the shallower parts.

Carbonate muds occur along the east coast, in places of low hydrodynamic intensity (i.e

[1] Sovremennye osadki Kaspiyskogo morya

with gentle waves and/or currents). Calcium carbonate content varies from 40 to 80 percent here, while farther west it decreases to 15 percent or less of the sediments. Oölites are largely confined to the shallow east coast but also occur on the west coast at Apsheron peninsula. They are found in "high hydrodynamic" areas, with vigorous waves and sea currents. Oölites have shell or silt nuclei; by abrasion of projecting points and growth of oölitic coats, they become more round and eventually become spheres. Thus oölites are formed in moving waters. In spotty areas occur carbonate crusts stained with iron and manganese oxides; these are irregular, slab-like, with entrapped sand, oölites, shells, etc., but oölites form the bulk of the rock. Iron- and manganese-stained zones contain dolomite, recognized by X-ray; the iron and manganese moved up from below. Crusts were formed by more rapid local precipitation of calcite, and the high alkaline content favors formation of crusts as well as precipitation of dolomite. Crusts occur in zones of moderate wave energy.

The paper provides a good detailed description and ideas on the early diagenetic formation of the calcareous crusts which are something of local importance and rather more of a curiosity than a general phenomenon. The section on oölite genesis contributes nothing beside the standard ideas.

M. V. Klenova, MATTER IN SUSPENSION IN THE KURA RIVER, p. 151-174, 6 figs., 12 tables, 14 refs.

The Kura enters the Caspian from the west, draining the Caucasus Mountains; it contributes more sediment to the Caspian than any other river, and the Kura is one of the most turbid rivers in the world. Samples of the river water were collected at six geographic stations, during each of three seasons. Measurements were made of total suspended matter, and also of the amount of material finer than 0.01 mm. Chemical analyses were also made of these sediments, and Klenova traces the changes downstream and with the seasons in a very detailed, descriptive fashion. Some data on bulk mineralogy and accessory minerals are also given; the sand is rich in feldspar. Some carbonate is precipitated when the material encounters Caspian sea water.

This is a thorough study of the chemical, mechanical and mineral composition, in rather stupefying detail; however it would be valuable for one who wishes to know the variation in these constituents in response to flood versus low-water periods. I consider the paper, however, to be a rather routine and tedious description of a local area rather than an illustration of new principles or ideas.

N. M. Arutyunova, MINERAL COMPOSITION OF THE BAKU ARCHIPELAGO SEDIMENTS, p. 175-185, 1 fig., 7 tables, 11 refs.

The author first reviews the several heavy mineral provinces of the Caspian, citing earlier works. The sediments are dominantly arkosic sands with abundant rock fragments, and the heavy mineral suite is complex. Sediments in the coastal area (about 100 miles long) are divided into several mineral provinces; in general feldspar and heavy minerals increase southward at the expense of quartz. This is a paper of local importance only.

P. G. Popov, "STRATIFICATION OF SEDIMENTS IN THE CASPIAN SEA, p. 186-241, 13 figs., 18 tables, 35 refs.

Popov first reviews the surroundings of the Caspian and touches on its changes in level, mainly influenced by amount of discharge of the Volga. Cores averaged about two feet long, and Popov divides them into zones based on sand: mud ratio, using the classification of Klenova; shell content; and color. Layers contributed by the Araks River can be recognized by their reddish color. More shells occur in layers interpreted as forming in shallower water. Average rate of deposition of sediments near the Baku archipelago is about 2.5 mm per year and from this the times of lowered Caspian level can be computed.

Mechanical analyses were made and presented in histogram form, using the very irregular class intervals of 1 mm, 0.1 mm, 0.05 mm, 0.01 mm. Near the islands occurs a bimodal mixture of very fine sand and clay, with not much silt; these are believed to be caused by erosion of the bottom. Farther from the islands, the upper layer is mud, and sand occurs at depth in the cores, indicating that the present Caspian level is higher.

The percentages of alumina, iron oxide, lime, magnesia, and sulfate were determined. Samples with abundant material finer than 0.01 mm were also high in alumina and iron oxide; coarser-grained samples were higher in lime. Mineralogically, the samples contained chiefly quartz, feldspar, clay and carbonates. Pyrite increased downward, and the heavy mineral suite is complex. Microfauna contains both contemporary and reworked specimens.

Some cores in the deeper middle part of the Caspian were also studied; these are largely clayey mud but coarser layers are attributed to periods of lower Caspian level. Diatoms were common in the cores. Detailed descriptions of these cores are given.

This paper, although largely a detailed description of various layers in the cores, is an interesting one to show the methods used for estimating levels of the Caspian by grain size

and shell content of the sediments at various levels in the core.

M. V. Klenova and L. A. Yastrebova, SEDIMENTS IN THE NORTHERN PART OF THE CASPIAN SEA, p. 242-271, 7 figs., 16 tables, 55 refs.

The northern Caspian is very shallow, and features the Volga and Ural deltas, and a trench cut by the Ural River when the Caspian stood at a lower level. There is a good discussion of changes in level of the Caspian and its effects on shorelines. A map of bottom sediment distribution shows that the bulk of the northern Caspian is floored by sand, with some areas of sandy silt; shells are widely distributed and coquinas are found in the south. Most of the sediments are pale gray or green.

The lack of many frosted grains points to insignificant contributions of windblown material, so the authors claim.

Organic carbon, nitrogen, and carbon dioxide were determined, with the carbon content carrying directly with content of fines. Most of the organic material is contributed by phytoplankton.

The paper is a good general summary, however no particularly new ideas are contributed.

V. P. Baturin and E. K. Kopylova, GEOLOGY OF THE SOUTHERN AND CENTRAL PARTS OF THE CASPIAN SEA (written in 1936 but not published), p. 272-302, 11 figs., 17 tables, 42 refs.

Although this article is old, I think it is the one most worthy of publication. The authors first discuss the structural outline of the Caspian coasts and the several raised terraces, partly the result of independent structural behavior of areas like the Caucasus. Submarine topography is very broadly outlined, as is the direction of currents (mostly counterclockwise in the central and southern Caspian). Next, the authors consider the material contributed by rivers; the Volga brings in 3/4 of the water, but the bulk of the sediment is contributed by the Terek and Kura which drain the Caucasus. There is a little quantitative data on the contribution of wind-blown material.

In studying the bottom sediments, the Caspian bottom sediments are mapped on the classification set up by Klenova (1931) which is based on the amount of material finer than 0.01 mm. The following classes are used:

	Percent finer than 0.01 mm
Muddy clay	50-100
Mud	30-50
Carbonate mud	30-50 (20-50 percent or more $CaCO_3$)
Sandy mud	10-30
Muddy sand	5-10
Sand	0-5

Using this system, mud occupies the bulk of the Caspian floor grading to sand around the shoreline, with some carbonate mud along the shallow eastern part of the Caspian. For each one of these sediment types, the authors describe the color verbally and give some more detail on the size distribution. In size analysis, each sample is divided into five fractions (over 1mm, 1 to 0.1, 0.1 to 0.05, 0.05 to 0.01, and finer than 0.01 mm) and the results are plotted as histograms. Each main sediment type (e.g., muddy clay) is then divided into two or three subtypes based on intuitive examination of the histograms — for example, whether the columns form ascending "stairsteps", or show two modes with a "sag" between, etc. The bulk of the paper is a description of the occurrences of the several sediment types. Shell and oölite sands ("pseudosands") occur along the east coast, and silts on the Caucasian coast. Areas of shells also occur, showing some zonation of taxa with depth of water. Some pebbles occur in deep water, derived probably from submarine outcrops.

The authors next discuss briefly the regional distribution of calcium carbonate in the sediments. The Caspian muds contain pyrite, but the uppermost layer is oxidized and brownish, due to oxygen-laden bottom currents. Several chemical analyses of the muds are presented.

The paper is a good general summary of the bottom sediments of the Caspian. The most important part of the paper is the maps, and there is not much discussion of the significance of the data other than platitudes about coarse sediments being in shallower water.

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My overall impression of this book is that it is a competent detailed job in certain respects, but that most of the papers are "what" papers rather than "how" or "why" papers. The bulk of the work consists of routine analyses done to show which heavy minerals occur where, or how alumina content varies with increasing content of fines, etc. There are few attempts at second-order analysis, e.g. plots of heavy mineral composition versus grain size, or faunal content versus depth of water. Analysis of the physical properties of the sediments is not very penetrating, for example the heavy minerals are simply listed without description, little or no mention is made of shapes of sand grains, degree of wear of microfossils, and only a half dozen of the major chemical constituents receive much attention. Size analysis seems to be extremely primitive, as the grain-size classes are very uneven (1, 0.1, 0.05, 0.01 mm) and all interpretation is done by visual inspection of the histograms. There is a complete lack of statistical analysis of either size, mineral, or faunal data. There are no new techniques introduced, nor are there many striking ideas. Most of the work seems tradition-bound — i.e. all papers use

the size-classification method shown above, published by Klenova in 1931. Virtually no non-Soviet references are cited.

The papers are of great importance to those who wish to know what is going on in the Caspian, but I feel they are of very little interest to those who are interested in new techniques or important new ideas. If this is an adequate sample of Soviet marine geology, then Scripps is about as far ahead of the Russians as their Sputniks are ahead of ours.

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EDITOR'S NOTE

On the basis of Dr. Folk's review and estimate of highest general reader interest, International Geology Review will carry the full translations of the following three papers from this symposium volume in subsequent issues:

SEDIMENTATION OF THE CASPIAN SUBMARINE SLOPE WITHIN AZERBAIJAN, by M. V. Klenova, p. 7-117.

SOME CARBONATE SEDIMENTS IN THE CASPIAN SEA, by V. F. Solovyev, p. 137-150.

GEOLOGY OF THE SOUTHERN AND CENTRAL PARTS OF THE CASPIAN SEA, by V. P. Baturin and E. K. Kopylova, p. 272-302.

The five other papers in the symposium have been translated. Individual copies may be purchased from the Translations Office, American Geological Institute, 2101 Constitution Avenue, N. W., Washington 25, D. C. at $0. 15 per translation manuscript page. The number of pages comprising the translation is tentatively indicated for each paper.

PECULIARITIES OF DIFFERENTIATION OF THE PRESENT CASPIAN SEDIMENTS IN THE REGION OF APSHERON, by V. F. Solovyev, p. 118-136 [61 pages of manuscript].

MATTER IN SUSPENSION IN THE KURA RIVER, by M. V. Klenova, p. 151-174 [70 pages of manuscript].

MINERAL COMPOSITION OF THE BAKU ARCHIPELAGO SEDIMENTS, by N. M. Arutyunova, p. 175-185 [36 pages of manuscript].

STRATIFICATION OF SEDIMENTS IN THE CASPIAN SEA, by P. G. Popov, p. 186-241 [100 pages of manuscript].

SEDIMENTS IN THE NORTHERN PART OF THE CASPIAN SEA, by M. V. Klenova and L. A. Yastrebova, p. 242-271 [78 pages of manuscript].

Reference Section

RUSSIAN AND EAST EUROPEAN GEOLOGIC ACCESSIONS OF THE LIBRARY OF CONGRESS

This section is devoted to a listing of selected geologic items appearing in the two publications of the Library of Congress; Monthly Index of Russian Accessions, and East European Accessions Index. These lists are intended as a means of indicating to researchers in the earth sciences some of the material most recently available for screening, further review, and translation. For this reason the lists do not include material now, or soon to be, published in English. Emphasis is placed on Russian material; the extent to which items from East European sources are listed depends on the country and language involved.

A major function of the AGI translations program is the screening of foreign literature for material that should be made available to the English-speaking scientist. Researchers who need such material are urged to review these lists and send us their recommendations for consideration by the editors; the translation needs of all geologists will be served better thereby.

-- Managing Editor

MONTHLY INDEX OF RUSSIAN ACCESSIONS

Volume 14, No. 1 April 1961

PART A—MONOGRAPHIC WORKS

12. GEOGRAPHY & GEOLOGY

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